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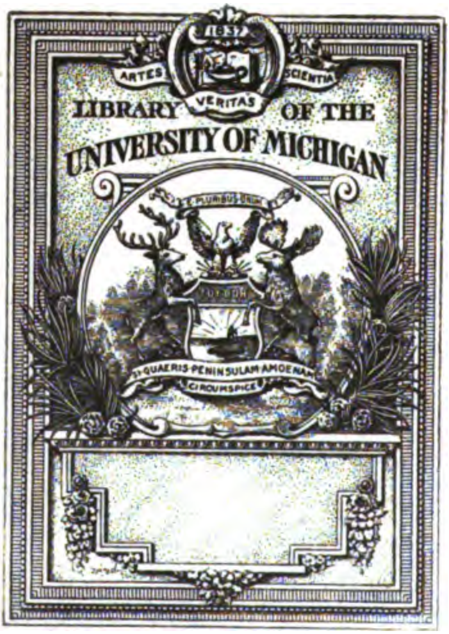

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GEOLOGY

"That delightful labour of the imagination which is not mere arbitrariness, but the exercise of disciplined power—combining and constructing with the clearest eye for probabilities and the fullest obedience to knowledge; and then, in yet more energetic alliance with impartial Nature, standing aloof to invent tests by which to try its own work."—GEORGE ELIOT.

E. A. Russell,
Columbia Coll.
1877.

GEOLOGY

For Students and General Readers

PART I.
PHYSICAL GEOLOGY

lexander enry

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TO THE

Memory of

THE REV. W. H. COLEMAN

MY FIRST TEACHER IN GEOLOGY

Yours faithfully
A. H. Green

Received [illegible], 1-26-35

151661

PREFACE.

THE Science of Geology, though barely yet a century old, covers already so wide a field and takes in so great a diversity of subjects, that few, if any, men can hope thoroughly to master the whole of it.

Mineralogy, Petrology, Stratigraphical Geology, Terrestrial Cosmogony, Palæontology, and other lines of research, though they may fairly be looked upon as subdivisions of Geology, are fast becoming separate Sciences.

But while it has become almost an absolute necessity for most Geologists to concentrate their attention on some one department of the Science and be content with a less perfect grasp of the rest, there is yet a certain basis or groundwork, with which every one who meddles with Geology, whatever be the branch to which he specially devotes himself, must be acquainted if his work is to be sound. For want of a knowledge of this groundwork the Petrologist, looking merely to chemical and mineralogical composition, classes together rocks which differ totally in their origin or manner of occurrence; the Palæontologist pure and simple is apt to force into an unnatural connection, on account of similarity in fossils, formations which physical evidence shows ought to be kept widely apart; the Field Geologist is content with tracing boundaries on his map, and forgets to ask himself how his lines were produced and what they mean.

It is this fundamental groundwork of which I have attempted to give an outline in the present volume, and in default of a better name I have called it Physical Geology.

I have had it in my mind to produce a book which will supply the requirements of two classes of readers.

I wished to draw up a manual which would serve the purpose of those students who, without going very deeply into the subject, desire to know as much of the Science as any man of culture may be reasonably expected to possess. To be familiar with only thus much of Geology affords many opportunities of agreeable intellectual amusement, for some of its branches, such as the connection between the scenery of a country and its geological structure, can be understood without any special knowledge, and may be mastered and enjoyed by any one who can use his eyes, and reason in a very common-sense way about what he sees around him.

But I have been still more anxious to produce a text-book for the School and Lecture-room; and in the hope that the book may be found suitable for educational purposes, I am tempted to venture a few remarks on the rank which Natural Science is entitled to hold as an instrument for training the mind to reflect and reason, a subject just now of somewhat brisk controversy. As a means of cultivating the faculty of observation its superiority is unquestioned; but it is not so generally allowed that it is as powerful an engine for developing the reasoning powers as the older studies of Mathematics and Classics. If Natural Science is ever to take rank beside these, it must show that it is equal to them in this very important respect; and any work on Natural Science, which is intended for educational use, must not only state clearly the results arrived at, but must also put forth the methods by which they have been obtained. For this reason I have dwelt, with I hope not wearisome minuteness, on the logical processes by which the conclusions of Geology have been reached.

One point more perhaps deserves notice. In spite of the elementary character of the work, I have not thought it desirable to shut out altogether those speculative branches of the subject, in which we are at present only feeling our way darkly along, and have not yet been able to arrive at any conclusion whatever. It has been objected to Natural Science in general, and the objection applies with special force to Geology, that it is unsuited for an instrument of education, because much of it is uncertain and liable to be upset by new discoveries, and much of it at present little more than a blank. But it is this very circumstance which seems to me to constitute one of the chief claims of Science to rank high among educational tools. The multiplicity of its unsettled points causes it to make constant calls on the imagination, and so to fill a corner hitherto unoccupied in the educational programme; for the results of Mathematics are too certain, and those of Classics too stereotyped, to leave much scope for imaginative ingenuity. In short, let us have Mathematics with its severe logic to develop our reasoning faculty, Literature and Art with their elegancies to form our taste, and Natural Science with its vexed questions and unsettled problems to stimulate and at the same time guide our imagination,* and we shall have a curriculum with every requisite for developing the intellect all round, and producing that highest result of culture, a many-sided mind.

A work like this affords little scope for originality, and I doubt whether there is in the book a single thing from beginning to end that can be said to be new. I have borrowed right and left; in many cases my obligations are so obvious, that it would have been unnecessarily burdening the pages with references to have acknowledged the sources of my information; in fact I have as a rule given references only in those cases where I wished the student to go more fully into the subject than I had room for. But whether I have recognised my debt or not, I beg to offer my best thanks to those numerous brethren of the hammer of whose labours I have availed myself without scruple and without stint.

I must also content myself with a general acknowledgment of the not inconsiderable help I have received from private sources; but I cannot forbear offering my special thanks to my father for his assistance in the revision of the proofs, and to my friend Mr. L. C. Miall for a similar service, as well as for a host of suggestions which have had the effect of materially adding to any value the book may possess.

---

* I would not be understood to mean that this is the only function of the study of Natural Science, or this the only way in which the imagination may be awakened.

Leeds, *January*, 1876.

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CHAPTER I.

THE AIM AND SCOPE OF GEOLOGY, WITH A SKETCH OF ITS RISE AND PROGRESS.

> "Signaler les efforts par lesquels ont été graduellement conquises les idées théoriques que nous possédons aujourd'hui n'est pas seulement un juste hommage rendu à ceux qui ont éclairé la science par leurs travaux: c'est aussi un avertissement salutaire contre les illusions spéculatives."
> Daubrée.

THE thing aimed at first of all by Geology was to find out what the earth, on which we live, is made of. It is probable that the earliest cultivators of the science did not set themselves to do any more than this, and that the only objects they had in view were, the examination of the materials out of which the solid framework of the earth is built up, and the determination of their chemical composition, physical properties, manner of occurrence, and other characteristics. True these pioneers had from time to time—indeed men of their acuteness could scarcely fail to have—glimpses, from the outskirts where they were labouring, of the wide geological domain that lay beyond; but for a long lapse of time the attempts to push onward into it were few and desultory.*

Geology then began, as all sciences must begin, by being a bare record of observed facts. But Geology could not, any more than other sciences, stop here. Some of the inferences to be drawn from these facts stare us in the face so palpably that they could not long escape notice. Among the facts, which in this way told their own story, one of the most obvious and the first to attract attention was the occurrence in the heart of solid rocks, and at spots far inland and high above the sea level, of what were undoubtedly the remains of marine animals. Two most important inferences followed from this: 1st, the rocks could not always have been there, but must have accumulated round the remains they now enclose; and, 2ndly, the arrangement of land and sea must have once been different from what it is now. In this way men came to learn that the earth had not sprung into being exactly as we have it now, but that changes had passed over it from time to time; and then there arose a further branch of Geology, which had for its object to determine *what these changes had been, and how they had been brought about.*

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* See Lyell, Principles, vol. i. chap. iii., for an account of the causes that hindered the advance of Geology.

The doctrine that the earth had been subject to change, which constitutes the very marrow of Geology, was established in the manner just described at least as far back as the days of Pythagoras, but it was long before the science made any advance beyond this and a few elementary truths of a like nature. The attempts made to give any rational explanation of the way in which the changes had been effected were only partly true, or were wholly erroneous. Some geologists failed on account of limited experience; they looked upon the tract they were acquainted with as a type of the whole globe, and their explanations, though well suited to local instances, were not of general application. Others were hampered by preconceived notions that geological changes had been produced all at the same time, and all by the same cause; Noah's Deluge, for instance, was a favourite resource with this school, and was credited with far more important results than it could possibly have effected, even if the popular notion of it were correct. A third class, the most mischievous of all, "took not their material from Nature, but spun it out of themselves;" they discarded observation altogether, and amused themselves with weaving ingenious conceits as to how the earth might have been brought into its present shape; and, when they found themselves in a difficulty, did not hesitate to call in to their aid agencies the like of which had never either been seen or heard of, and the like of which, as far as our knowledge of the economy of Nature goes, could never have been in operation. The wild dreamy speculations of this school, with their convulsions, cataclysms, inundations, collisions with comets' tails, and other fanciful occurrences, read like a translation of a Scandinavian saga without the life of the original, and it is really hard to believe that they could ever have been seriously put forward by men calling themselves scientific students. Among the other causes which hindered the progress of the science, we may specially mention a dreary controversy, which dragged its slow length along over more than a century, as to whether the things in the rocks, which appeared to be organic remains, ever had belonged to living animals, and were not rather counterfeits, moulded by Nature in some elfish mood purposely to lead mankind astray. It is scarcely believable that so impudent a notion could ever have found supporters; but it did, and no lack of them either.

The early history of Geology then consists of a record of one long string of failures, but the study of these will be by no means barren of results, if we look at them from the right point of view. When we see men of unquestionable power going on for centuries missing the mark, the only conclusion we can come to is that there was something radically wrong in the way in which they went to work. And it is easy enough to see what it was that was wrong in their method. If we want to learn how a piece of furniture, a pair of shoes, or a coat is made, we don't sit down and waste our time in barren guesses and random shots, but we go to the cabinet-maker, the shoemaker, or the tailor, and watch them at their work. Nor will one visit be enough; if we wish really to get to the bottom of the matter, we must go again and again, till we have made ourselves masters of every step in the process of manufacture. Just so, if we want to learn how any natural product arose, we must haunt the workshop of Nature, till, by long and repeated study, we wring from her the secrets of her trade, and gain an insight into every step of her complicated and manifold operations. Now this is just what the earlier geologists did not do. Some observed, but did not observe enough; others shirked altogether the labour of observation, and tried to supply its place by speculations, which had nothing but imagination to rest upon.

Practically, in spite of some advances every now and then in the right direction, Geology continued in this unsatisfactory state down to the end of the last century. Then there came on the stage Hutton, the kind of man the science had so long been in need of, and by his teaching geologists were at last started on the only path that could possibly lead them to truth. He pointed out, in words that could not be misunderstood, that, if we want to know what has happened on the earth in bygone times, we must begin by learning what is going on there now. He drove out once and for ever the imaginary agencies, which the earlier geologists had been so ready to have recourse to; and laid down the principle, that in geological speculation "no powers are to be employed that are not natural to the globe, no actions to be admitted of except those of which we know the principle, and no extraordinary events to be alleged in order to explain a common appearance."* Following out this principle, he said something like this: You have here a rock, and you want to know how it was formed. Well, what you must do, is this. You must go and search whether there is anything now in the course of formation which is either identical with that rock or could be made identical with it by processes which we know Nature is capable of employing. When you find such a substance, learn what are the agents that are forming it. It will then strike you irresistibly that it is far more likely that your rock has been formed by agencies similar to those which are now producing a substance that cannot be distinguished from it, than that it was made by some imaginary, unheard-of, and improbable process. And Hutton laboured successfully to show that the forces now in action are fully competent to form rocks, and to bring about a large portion of the changes, which we learn from Geology must have passed over the earth's surface. Here he stopped, confining himself to that portion of the earth's lifetime during which her physical condition has been similar to what it is at present; it is somewhat doubtful whether he even realised the probability of there having been a time when the earth was in a very different state from now; but, if he did, he declined to concern himself with the events and operations of such a period. It cannot be denied, then, that Hutton took rather a narrow view of the scope of Geology; but in the portion to which he applied himself he may fairly be looked upon as the veritable father of the science; and since the history of the earth as it is must be mastered before we can go on to unravel the history of the earth as it was before the present state of things was established, we may go further and call him the founder of Geology as a whole.

Hutton, like most great men, was in advance of his age; his teaching fell dead† till it was revived and illustrated by Lyell; but it is now universally recognised as the principle on which we must base all speculations relating to that part of the science of which he treated.

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* Theory of the Earth, ii. 547.

† How completely this was the case may be seen from the following passage, which sounds strange to the geologist of to-day: "The theory of Hutton has gradually sunk into disrepute in proportion as geological facts and observation have been more multiplied

Hutton occupied himself mainly in studying the changes that are now taking place on the earth's surface, and the means by which they are being brought about, and in demonstrating that the changes that had happened during past periods of the earth's history were of the same kind and due to the same causes as those now going on. He could not fail to realise clearly the fact, known before his day, that rocks were not all of the same age, and he describes* with rugged eloquence observations which showed him that some of the older rocks had been displaced from their original position and had suffered wear and tear before rocks of later date had been laid down upon them. But he did not go beyond these broad general facts, nor attempt to determine with any detail the order in which rocks had been formed. The first steps in this direction, sufficiently systematic to call for notice here, were made, about the same time, by two contemporaries of Hutton, Werner and William Smith.

The former showed that the rocks of the part of Germany which he examined could be divided into certain groups, and that these groups came on, one over the other, in an order of succession which was everywhere the same. Thus if we call these consecutive groups *a*, *b*, and *c*, and note in one place that *a* is the undermost, *b* the middle, and *c* the uppermost of the three, we shall find these groups in the same relative position with regard to each other wherever we meet with them; *b* will never be below *a* or above *c*. The same law holds good throughout the whole series of groups. Some members may be wanting in places, but this will not affect the place in the series of the rest; thus, if *b* be absent, *c* will rest on *a*, never *a* on *c*. Some of Werner's subdivisions agree pretty nearly with those of modern geologists; others have been long ago discarded, because they were established on the strength of erroneous theories as to the way in which the rocks composing them had been formed. These theories were of the wildest description, wholly unsupported by observation or analogy,

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and extensive; and it is not improbable but even the beautiful theory of Werner may share a similar fate, as some parts of it have met with considerable and powerful opposition."—WESTGARTH FORSTER, *Section of the Strata* (1821), p. 153.

* Theory of the Earth, vol. i. chap. vi.

and, as they were put forward with a zeal and energy which gave their author great influence over his pupils, they contributed no little to hinder the progress of Geology. Still it was a great step gained to have established the fact of the existence of an invariable order of succession in the rocks.

While Werner was pursuing his investigations in Germany, William Smith was patiently at work among the rocks of England, paying special attention to the fossil remains of plants and animals which they contained. He found that the law which Werner had established for the succession of rock groups in Germany was equally true for those of this country; they were laid one upon the other in an order which was everywhere the same. His study of fossils enabled him to establish a further law of the greatest importance. He discovered that each rock group contained a number of fossils different from those in any other group, and that by means of these fossils it could be recognised and its place in the series determined, in cases where this could not be accomplished in any other way. Thus, suppose that we determine at any one spot the order in which the three groups, *a*, *b*, and *c* occur, and note and record the fossils found in *b*; further, that at another spot we find rocks containing the same fossils as *b*, but cannot see what is below or above them; then, on the strength alone of the similarity of the fossil contents of the two rock groups, we may safely assert that these problematical rocks belong to the *b* group, and that below them there is either *a* or something lower in the series, and above them either *c* or something higher.

From the first of the two laws just mentioned it was an easy step to show, as we shall see shortly, that the place of each rock group in the series gave the relative date of its formation, that the lowest was the oldest, the one above came next in point of time, and so on. From the second law we learn that the changes which had passed over the earth had not been confined to the inorganic portion of it, but had affected its living inhabitants as well; that each period of its past history had had its own peculiar forms of life, and that these had from time to time died out and been replaced by new forms.

Then there arose a further branch of Geology, which had for its objects to determine not merely what changes had happened formerly on the earth and how they had been brought about, but *also the order in which they had occurred;*

and further, to describe the different living forms which had peopled the globe in former ages.

These then seem to have been the main steps in the progress of Geology. It began merely with the view of making out what the earth was made of—with being merely a science of description and classification. Then in the pursuit of this study facts came out which told a story of former changes that had passed over the world, and geologists set to work to discover what these changes had been, and how they had been caused. Lastly, it was found possible to determine the order in which past changes had occurred, and the modifications in the forms of life by which they had been accompanied. The methods employed for these ends advanced Geology to the place of an inductive science, and their results enlarged its scope and gave rise to what may be called its historical branch.

Thus there arose two main subdivisions of the science, which may be called Descriptive and Historical Geology; and these it is still convenient to retain. One object in giving the preceding sketch of the progress of the science has been to show that these are not mere arbitrary or even convenient divisions, but grew up with the growth of Geology itself.

We have already mentioned that, even in its early or descriptive stage, many of the cultivators of Geology had foretastes of what it would afterwards grow to; but the labours of Hutton and Smith, specially those of the former, may be said to have raised Geology, practically at one step, from a bare record of observations to the dignity of an inductive science. Since their time it has grown apace, and no science can boast of a more rapid development.*

The student will do well to mark that the great advance made by Hutton and Smith was won by systematic hard work in the field; and he must bear in mind that no further progress can be made except in the same way: what may be called laboratory work, indispensable as it is, avails little or nothing in Geology, unless it rest on the firm basis of field investigation. Observations made out of doors need to be followed up by indoor work, if we are to interpret them aright, but Geology is fundamentally an open-air study.

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* For more particulars as to the history of Geology, see Lyell's Principles, vol. i. chaps. ii.—v.; Phillips, Manual of Geology, chap. i.; Conybeare and Phillips, Geology of England and Wales, Introduction. Carl Vogt, Lehrbuch der Geologie und Petrefactenkunde, vol. ii. 682—747. Daubrée, Etudes sur le Métamorphisme. Mémoires présentes à l'Académie des Sciences, tome xvii.

Before going further, it will be well to inquire how much of the earth lies sufficiently within our ken to be properly the subject of geological investigation. Sea and river cliffs, the beds of brooks, quarries, railway cuttings, and other artificial openings, show us what is found to a small depth below the surface, and mines enable us to feel our way a little lower down still; but the portion of the earth's mass that we can examine by these aids alone, is evidently very small indeed.

We can, however, from observations made at or near the surface, infer, with a very high degree of probability, what the composition of the earth is at depths far exceeding that of the deepest mine.

Suppose, for instance, that we had proved, say by the mine shafts *A B C*, the presence of the three groups of rocks marked *a b c*, in Fig. 1, and had found them always to come on one over the other in the same order, and to keep a regular thickness over a considerable area; it is highly probable that these rocks, when beyond *C* they pass out of our sight, will preserve the same order and thickness in their underground course. Assuming this to be the case, a very simple calculation will give us the depth of any one group at a point *E*, and we can thus form a very probable conjecture as to the composition of the earth at a point such as *E* far below the bottom even of the deepest mine. In this way Van Decken has found that in parts of the Coal-basin of Saarbrucken the character of the rocks may be determined to a depth of more than three miles below the surface. In reasoning on a case of this sort we should feel still more confident in our

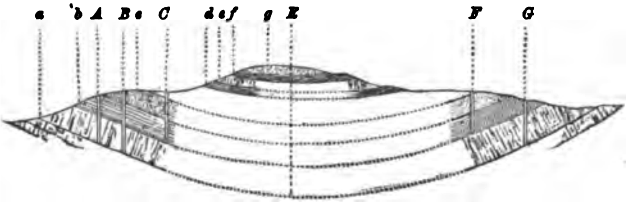

Fig. 1.

conclusion if we found, as we often do find, the same groups of rocks reappearing in the same order from below, as in the shafts at *F* and *G;* and we should then have little hesitation in showing their underground course by some such lines as the dotted ones in the figure. We should be able to determine with more accuracy the shape of these underground continuations if we could observe in the intermediate ground higher rocks, such as *d e f*, and *g*, and determine how they are lying. Thus, as Playfair remarks, "men can see much further into the interior of the globe than they are aware of, and geologists are reproached without reason for forming theories of the earth, when all they can do is but to make a few scratches on the surface."*

Still, when we have pushed our investigations to the greatest depth, that either direct observations, or reasoning that flows immediately from them, enable us to reach, we shall have made ourselves acquainted with no more than an outside shell or rind, not more than a few miles at the most in thickness.

This shell, because it is so thin, is called the crust of the earth, and with it Geology is first of all of necessity concerned.

But Geology need not stop here. When we have gathered some knowledge of the crust of the earth, we are naturally led on to make this knowledge a basis for speculations about the nature of those inaccessible regions which lie below the crust. And when we have got together something like a history of the formation of the earth's crust, we are prompted to inquire whether there ever was a time when our planet was without a crust, what was its condition at that time, and how it passed from that condition into its present state.

We shall see presently that as long as Geology confines itself to the crust of the earth, it is dealing with something corresponding to written records in history, and that the story these tell, is so clear and unmistakable that many of its conclusions are as certain as those of any other of the natural sciences; but that, when it comes to treat of the inaccessible interior, or the history of the earth before it assumed its present state, there is nothing of the nature of a written record to guide its speculations, it has to lean mainly on a scientific use of the imagination, with little or no check from actual evidence, and its conclusions consequently cannot rise above the rank of probabilities.

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* Works (ed. 1822), vol. i. p. 244.

Some geologists would limit Geology entirely to a study of the earth's crust, others take the wider view of its scope just given.*

It will be seen that even in the more speculative parts of Geology we do not indulge in mere conjecture, but work persistently back from the seen and known to the unseen and unknown. We do not try to form any idea about the probable constitution of the invisible interior, till we have made ourselves acquainted with the visible outside crust; and we do not theorise about that part of the earth's history of which no tangible record is left, till we have diligently studied those later epochs of which some sort of written account has come down to us.

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* See Professor Huxley's Anniversary Address to the Geological Society of London. Quarterly Journal, vol. xxv.; and Geological Magazine, vol. vi. p. 275.

CHAPTER II.

DESCRIPTIVE GEOLOGY.

> "In the corner of the hall stood a box of stones. Many pretty eye-catching things were among them."
>
> WILHELM MEISTER'S TRAVELS.

SECTION I.—GENERAL RESULTS ARRIVED AT BY A LITHOLOGICAL EXAMINATION OF ROCKS.*

WE showed in the last chapter how, with the growth of Geology, there sprang up two main subdivisions of the science, to which the names of Descriptive and Historical Geology may be given.

Descriptive Geology or Petrography.—The first of these, which corresponds nearly with Petrography, merely tells us what that part of the earth which is open to investigation, is made of; and is nothing more than a description and classification of the substances that make up the earth's crust.

Historical Geology or Geogenie.—But as men passed from examining, dissecting, and analyzing specimens of rocks indoors, to the larger views which an outdoor study of those rocks on a large scale affords, they came to see that there was every reason to believe that the crust of the earth had not been always such as it is now, but that different parts of it had been built up at different times and in different ways out of pre-existing materials. Hence arose a second great subdivision of the science, which aims at answering the questions about the origin of rocks which extended study suggests. This branch of Geology, which is pretty much the same as the Geogenie of the Germans, strives to determine first of all how the different members of the earth's crust were formed; secondly, the order in which they were formed, and the changes in life and other events which accompanied their formation; and, thirdly, tries to feel its way back to those dark and distant ages, when the present crust of the earth had not yet come into existence, and to form reasonable conjectures as to what the earth was like under these conditions, and as to the steps it passed through in its progress from them to its present state. Under this subdivision we shall also have to inquire into the methods by which the rocks have been brought into the positions in which we now find them, and the way in which the surface of the ground has had its present shape given to it.

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* This chapter consists of a mass of dry details, which, for orderly arrangement, it was necessary to place together, but which the student will find it tedious to master and hard to carry in his head. He may, on first reading, confine himself to sects. 1 and 2, the descriptions of Quartz, Potash-Felspar, Mica, and Carbonate of Lime in sect. 3, and sects. 4, 6, and 7. This much will carry him through chaps. iii. iv. and v. Before reading chap. vi. he should go through the omitted parts of the present chapter.

We will in this chapter treat of so much of the descriptive part of Geology as it seems desirable to keep apart from its historical element.

Subdivisions of Descriptive Geology.—Descriptive Geology consists of two parts, which may be called Lithology (*λίθος*, a stone), and Petrology (*πέτρα*, rock).

Lithology.—Lithology describes the results which would be arrived at by a man who sat indoors in his laboratory, and examined small hand-specimens of different kinds of rock brought to him.

Petrology.—Petrology tells us what additional information we gain when we go out of doors and examine large masses of rock in the field.

The first of these gives us accurate information as to the composition and minute structure of rocks, but alone it does little or nothing towards explaining how they came into existence; indeed it is doubtful whether purely lithological studies would even suggest the idea of rocks ever having been in any way different from what they are now, and give rise to questions about their origin. Petrology, however, though it belongs in part to Descriptive Geology, lands us on the threshold of the Historical subdivision. The facts learned from it, many of them such as no amount of indoor examination of hand-specimens would ever have taught us, are decidedly suggestive of the notion that rocks have not always been such as we see them now, but have been produced at various times by various causes;

and it is mainly from a knowledge of these facts that our speculations as to the probable methods by which the rocks have been formed, take their rise.

What we have to say under the head of Lithology will, perhaps, be better understood if we first take one or two actual instances of the lithological examination of rocks.

Instances of the Lithological Examination of Rocks.—We have here a bit of the rock called Granite, and have formed a clean-cut face upon it with the hammer. A very little care will show that the rock is made up of different substances, three of which we soon learn to distinguish and recognise. One is of a dull white or pinkish colour, and it breaks readily along a number of smooth parallel surfaces, which have a pearly lustre; the second is more like glass to look at, and breaks with the same uneven fracture as glass; the third consists of thin plates of a dark colour, with glistening faces, and can be readily split parallel to these faces with a knife. These three substances go by the names of Felspar, Quartz, and Mica respectively. They are bound together into a solid rock by a cement or paste; but to make out the nature of this would require more skill than we are supposed at present to possess.

Here again is another rock, which we soon see is composed of rounded grains of the same substance, Quartz, as we found in Granite; we touch it with a little dilute acid, and it effervesces briskly; no such effervescence takes place when we treat Granite in the same way. In this rock, then, we conclude that there is something present which does not enter into the composition of Granite. Break the specimen open. There is in it a hollow space lined with glistening crystals, which, when touched with acid, effervesce even more strongly than the body of the rock itself, and are therefore probably formed of the other substance which goes to make up the rock. This substance is not unlike Felspar at the first glance, but we soon learn to distinguish between them: try to scratch both with the point of a knife, and Felspar is much the harder; Felspar does not effervesce with acids; lastly, while Felspar splits readily in only one, or at most in two directions, this substance splits with the greatest ease along three sets of smooth, shining planes, and can be readily broken up into a number of pieces, each of which has exactly the same geometrical form. Our new acquaintance is called Carbonate of Lime, and the rock we are examining consists of grains of Quartz bound together by Carbonate of Lime.

Now with regard to these substances, which we have found to form the component parts of the two rocks just mentioned, one point is important to notice. Though different parts of the specimen we first handled, differ slightly from one another in composition, some containing more Felspar than anything else, and some having a more plentiful supply of Mica than others, yet bits of the three substances of which the rock is made up, possess the same physical characters from whatever part of the specimen we pick them, and, if we subject them to chemical analysis, we shall find them to be approximately invariable in composition.

The same would be true of the second rock even to a greater degree; some parts of the rock would be richer in Carbonate of Lime than others, but every one of the bits of clean Carbonate of Lime that could be separated would be found to be absolutely identical in every respect, no matter what part of the rock it came from.

We have therefore found, in the case of the two rocks that we have been examining, that they are composed of certain chemical compounds, each of which has always pretty much the same appearance, breaks always in the same way, and keeps always the same hardness and chemical composition.*

Definition of a Mineral.—*Substances which possess the properties just mentioned, are composed of dead matter, and have been formed naturally, are called* MINERALS.

There are other rocks the constituent minerals of which are not easily recognised, and others which require very refined methods to determine what they are made of; but in all cases rocks can be shown to be made up of one or more of those substances to which the general term "mineral" is applied. The cases where large rock masses consist of only a single mineral are very rare in comparison with those where several minerals are mixed together to form the rock.

Definition of a Rock.—After repeated examinations of different kinds of rocks, like those just described, we arrive at the following definition of a rock.

Rocks are mechanical mixtures of certain inorganic substances,

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* It will be shown presently that these statements are in many cases not strictly true; but they may be looked upon as correct enough for our present purpose.

more or less definite in character and composition, known as minerals.

We may here mention that geologists include under the name Rock all the substances, hard and soft alike, which go to make up the earth's crust; clay or loose sand are as much rocks, in the geological sense of the word, as slate or sandstone.

SECTION II.—MINERALOGY.

The first thing which the lithologist has to do is to make himself acquainted with the minerals which enter into the composition of rocks; and the branch of Geology which teaches this is called *Mineralogy*.

Number of Rock-forming Minerals.—The total number of known minerals is very large indeed, but of these only a comparatively small number enter to any appreciable extent into the composition of the earth's crust, and with these only is it absolutely necessary that the geologist should make himself acquainted. Thus suppose, for instance, that we examined, in the way just described, a large number of specimens of Granite, we might find them all in the main made up of the three minerals Quartz, Felspar, and Mica; but besides these three predominating components, other minerals would frequently present themselves. In many cases, for example, we should detect, in addition to the three minerals just mentioned, long needle-shaped prisms of a black mineral known as Schorl. But the presence of Schorl would not prevent us from calling the rock a Granite, and looking upon it as allied to other Granites which were free from Schorl, or which contained other minerals in addition to the three normal constituents. We might use Granite in a *generic* sense, and look upon the schorlaceous and other forms of the rock as different species of that genus; or, what would perhaps be better, we might consider these last as merely varieties of the *species* Granite.

Minerals, such as the Schorl just mentioned, which are, as it were, superadded to the normal constituents of any rock, are called *accessory or adventitious;* the advanced student will find that a study of them often throws light on the origin of rocks, but a knowledge of them is not necessary for the beginner.

Again, the metallic ores, occurring as they do chiefly in narrow veins and threads, cannot be looked upon, except in some few instances, as rock-forming minerals. The mastery of these then the beginner may postpone till he has made some advance in his studies.

Besides these two classes there are a host of minerals seldom met with, and some so rare that no one but a mineralogist, who has the most extensive opportunities of research, has ever a chance of even seeing them; with these we may almost say that the geologist has nothing whatever to do; the beginner certainly need not trouble his head about them.

When we put aside the minerals which occur only as accessory constituents of rocks, the metallic ores, and the rare forms, the number remaining will not be large; and it is of these only that we need treat in an elementary work. But before we can give an account of these we must describe, as far as space will allow, the characters most important to note in minerals generally.

Chemical Composition of Rock-forming Minerals.—First of all, the chemical composition of minerals falls to be considered.

Chemists divide all bodies into two great classes: Compound Bodies, which it is possible to split up into two or more substances, differing from each other and from the compound formed by their union; and Simple Bodies, or Elements, which no one has yet been able so to split up.

The latter are sixty-three in number, but of them not more than nineteen, at the outside, enter to any extent into the composition of the rocks of the earth's crust.

The names of these nineteen elements, and the symbols used by chemists to denote each, are given in the table below.

The ten placed in the first subdivision form by their combinations perhaps as much as 977-1000ths of the whole crust; the two in the second subdivision come next in importance; the remaining seven enter in small quantities into the composition of some common rock-forming minerals, or replace in small quantities the normal constituents of these minerals, or are found in rock-forming minerals of only local occurrence.

LIST OF THE MAIN ELEMENTARY CONSTITUENTS OF THE EARTH'S CRUST.

Non-Metals.		*Metals.*	
Oxygen	O.	Aluminium	Al.
Hydrogen	H.	Potassium	K.
Silicon	Si.	Sodium	Na.
Carbon	C.	Calcium	Ca.
		Magnesium	Mg.
		Iron	Fe.
Sulphur	S.		
Chlorine	Cl.		
Fluorine	F.	Lithium	Li.
Phosphorus	P.	Barium	Ba.
Boron	B.	Manganese	Mn.
		Zirconium	Zr.

Of these elements two only, Sulphur and Carbon, occur simple or uncombined, in a state of approximate purity, as rock masses. All the other elements are found in combination, and the following are the principal primary compounds, which, either by themselves or in a state of further combination with one another, go to make up the mass of rock-forming minerals :—

1. *Water* (Hydrogen Monoxide) H_2O. When minerals contain water they are said to be *Hydrated;* when they are free from water they are described as *Anhydrous.*

2. Three acids :—

Silica (Silicon Dioxide) SiO_2.—By far the most widely diffused of the rock-forming minerals, nearly one quarter of the crust of the earth being composed of it. It occurs uncombined as Quartz, and in combination in silicates to be immediately noticed.

Carbonic Acid (Carbon Dioxide) CO_2.

Sulphuric Acid (Hydrogen Sulphate) H_2SO_4.

3. Next we may take the following group :—

Alumina (Aluminium Sesquioxide) Al_2O_3.

Potash (Potassium Monoxide) KO.

Soda (Sodium Monoxide) Na_2O.

Lime (Calcium Monoxide) CaO.

Magnesia (Magnesium Monoxide) MgO.

The silicates of these substances, with small quantities of Lithium, Fluorine, and Iron Oxides, make up the minerals which compose the rocks known as Crystalline.

The decomposition of some of these minerals gives rise to Hydrated Silicates of Alumina, which mixed with mechanical impurities constitute the different forms of clayey rocks.

The most important Lime compound is the Carbonate ($CaCO_3$), which forms the bulk of Limestone.

The double Carbonate of Lime and Magnesia ($CaCO_3 + MgCO_3$) is the main constituent of Magnesian Limestone or Dolomite.

Sulphate of Lime, or Gypsum, ($CaSO_4 + 2H_2O$), occurs as a rock, and the Phosphate ($Ca_3 2PO_4$) is not uncommon as an accessory mineral and in veins.

4. *Common Salt* (Sodium Chloride), $NaCl$, occurs as a rock.

5. Compounds of Iron. The following are the most frequent:—

Hæmatite or Specular Iron Ore (Iron Sesquioxide) Fe_2O_3.

Brown Hæmatite or Limonite (Hydrated Iron Sesquioxide), $2(Fe_2O_3)3(H_2O)$.*

Magnetite or Loadstone, Fe_3O_4.

Spathic Iron (Ferrous Carbonate) $FeCO_3$.

Silicate of Iron, $2(FeO)SiO_2$.

All these substances, except the last, occur now and then in sufficient quantity to form rock masses, and Magnetite enters in small quantities into the composition of many crystalline rocks. But the most prominent part iron compounds play is in furnishing the colouring matters of many rocks: generally the anhydrous sesquioxide gives rise to red tints of variable intensity; the hydrated sesquioxide produces colours ranging from yellow to brown; while the carbonate confers a grey or bluish grey hue. Many variations in tone are caused by mixtures of the different iron compounds, and other colours are produced by different amounts of hydration of the sesquioxide.† Impure Silicate of Iron is sometimes disseminated through sandy rocks in sufficient quantity to give them a green tinge.

Iron Pyrites (Ferrous Disulphide), FeS_2, is one of the commonest accessory minerals, and sometimes occurs in quantities deserving the name of rock masses. It may in some cases have furnished by oxidation the colouring matter of rocks.

6. *Baryta* (Barium Monoxide), BaO, enters into the

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* For other Hydrates of Iron, see Prof. Brush, Silliman's Journ., 2nd ser. xliv., 219.

† See Maw, "On the Disposition of Iron in Variegated Strata," and the papers referred to by him. Quart. Journ. Geol. Soc., xxiv. 351. Dawson, Ibid., v. 25.

composition of the very common mineral Barytes or Sulphate of Baryta.

7. *Zirconia* (Zirconium Dioxide), ZrO_2, appears as a Silicate (Zircon) in certain rocks.

8. *Boracic Acid* (Boron Trioxide), B_2O_3, may be noticed as a volcanic product.

External Form and Internal Structure of Minerals.—1st. Crystalline Forms.—The next points to notice about minerals are their external form and internal structure. They very frequently occur in the shape of regular geometrical solids, bounded by smooth shining faces. Such forms are called Crystals, and the study of them Crystallography.

The planes that bound crystals are called their "faces"; the intersection of any two faces is called an "edge"; and the point where three or more edges meet is called an "angle". The solid angles formed by the meeting of three or more faces are the solid angles of the crystal, and the inclination of two faces to one another is called an "interfacial angle".

Let us consider one or two actual cases of Crystalline forms.

Here is a piece of a mineral already mentioned, Carbonate of Lime or Calc Spar (Fig. 2, *a*). It is a solid bounded by smooth, glistening faces, each of which is a rhombus, and all these rhombuses are of exactly the same shape, that is, the corresponding angles are the same for every one. The solid is called a rhombohedron. Knock a bit off one

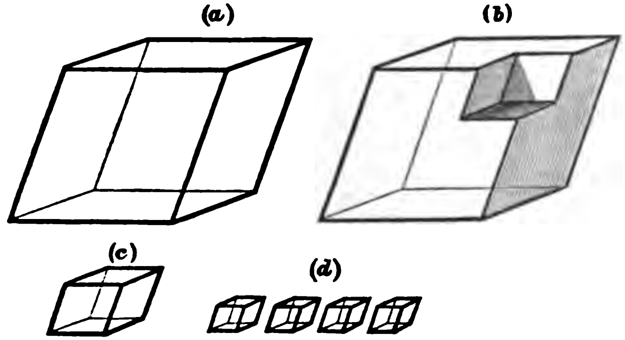

Fig. 2.

corner; it falls away in the shape of a rhombohedron, smaller than the one from which it has been broken off, but in every other respect exactly similar (Figs. 2, *b* and *c*). The rhombic faces of the detached fragment have their angles exactly equal to the corresponding angles of the rhombuses that bounded the original block, and the corresponding interfacial angles of the two specimens are exactly equal. Further, the bit we have broken off can itself be further broken up into rhombohedrons (Fig. 2, *d*), these again into still smaller rhombohedrons, and in every case the shape of the fragments will be identically that of the block we started with.

Cleavage.—This property which the mineral has of breaking more readily in certain directions than in others, and of breaking in these directions with a smooth face, is called Cleavage, and the smooth faces thus obtained are called Planes of Cleavage. We might by force make Calc Spar break in other directions than those of the Cleavage Planes, but the surfaces we should thus obtain would be no longer smooth and shining, but rough and dull.

But Calc Spar is found crystallised not only in the shape of a rhombohedron, but in hundreds of other forms besides. One of the commonest of these is called, from the pointed shape of the crystals, Dog Tooth Spar. Take one of these tooth-shaped crystals, tap it gently with the hammer, and it will fall into a number of rhombohedrons identical in every respect except size with those of our first specimen. This crystal, seemingly so different from the rhombohedron we were just now handling, is really built up of a number of elements agreeing with it exactly in their geometrical form. This will also be found to be the case with all the different crystalline shapes under which Calc Spar is found.

Fundamental Form.—The rhombohedron to which all crystals of Calc Spar can be reduced is called the Fundamental Form of the mineral.

Calc Spar has been chosen for the foregoing example because it cleaves readily parallel to all the faces of its fundamental form. In other crystallised substances cleavage can be obtained only in two or one directions; and in others not at all, or only with the greatest difficulty.

The student may also easily verify for himself another case in which one crystalline form may be made to pass into another by means of cleavage, viz. that of Fluor Spar.

This mineral is found frequently crystallised in cubes, such as Fig. 3, *a* If a knife be placed near one of the angles of the cube, touching the face *A B C D* in a line parallel to the diagonal *A C*, and equally inclined to the three faces that meet in *B*, and then firmly pressed against the crystal, a bit will fly off, bounded by triangular faces, and the crystal be reduced to the shape in Fig. 3, *b*. If each of the angles be treated in the same way, the whole crystal may be similarly modified. We shall then find that we may continue to split off slices parallel to faces corresponding to *a b c*, till the crystal is reduced to the shape in Fig. 3, *c*, which is a solid bounded by six squares, each of which is formed by joining the middle points of the edges of each face in the original cube, the dotted figure *e f g h*, in fact of Fig. 3, *b*, and eight equilateral triangles. By still further continuing the process the square faces grow smaller and smaller, till the crystal is at last reduced to the shape

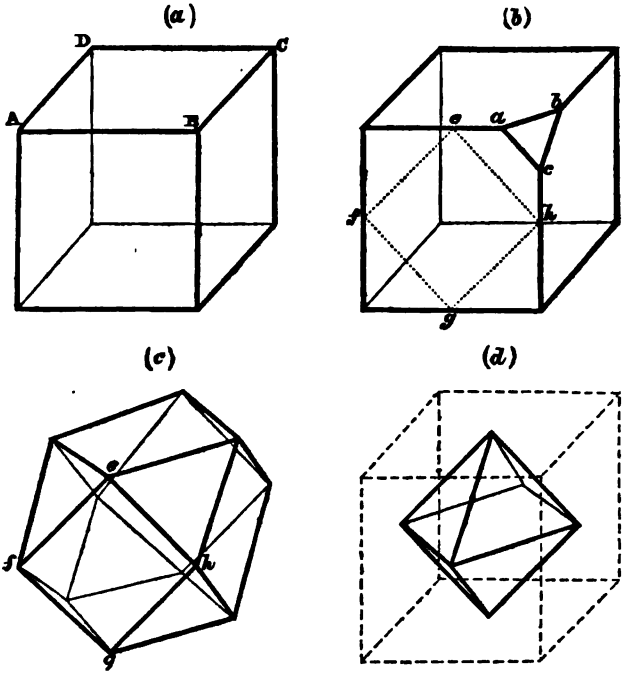

Fig. 3.

of Fig. 3, *d*, which is a regular octohedron, bounded by eight faces, each of which is an equilateral triangle. Each of the angles of the octohedron occupies what was the centre of a face of the original cube, the relative position of which is shown by dotted lines.

By similar reasoning to that just described it has been ascertained that all the multitudinous and complicated crystalline forms met with in Nature may be reduced to a few simple shapes, of which it is usual to reckon some dozen as fundamental.

These we will now describe, first adding to the definitions already given the following:—

Axes of Crystals.—"The Axes of a crystal" are imaginary lines, about which the crystal is symmetrically arranged. They connect either opposite angles, or the centres of opposite faces, or the middle points of opposite edges. We have, therefore, in any symmetrical crystal several sets of axes to choose between. The choice however is not arbitrary, that set being selected in each case which optical or other properties of the crystal prove to be related to its intimate molecular constitution.

Enumeration of Fundamental Forms.—The Fundamental Forms are as follows:—

1st. PRISMATIC FORMS.—If we take any two plane figures exactly alike in every respect, place them so that each side of the one shall be parallel to the corresponding side of the other, and then join the corresponding angles by straight lines, the solid so enclosed is a prism. The two similar plane figures are called "the ends", the other bounding figures, which it is easy to see must be parallelograms, are called the "lateral faces", and their intersections "lateral edges". The line joining the centres of the ends is called the "longitudinal axis"; the other axes, called "transverse axes", connect either the centres of opposite lateral faces or the middle points of opposite lateral edges. It is easy to see that the tranverse axes lie in a plane of the same shape and size as the ends.

Prisms are classed according to the shape of their ends; a prism with square ends is a square prism, one with hexagonal ends an hexagonal prism. Further, if the longitudinal axis is perpendicular to the ends, the prism is a "right prism"; if not, an "oblique prism".

Among the fundamental forms of minerals the following are prismatic:—

1*a*. RIGHT PRISMS.—Lateral faces rectangles; longitudinal axis, as it is easy to see, always perpendicular to the transverse axes.

The cube. Bounded by eight equal squares. The axes connect centres of opposite faces, are all equal and perpendicular to one another.

The right square prism. Ends squares. Transverse axes connect centres of opposite lateral faces, they are equal and perpendicular to one another, but not equal to the longitudinal axis.

The right rectangular prism. Ends oblongs. Axes connect centres of opposite faces, are perpendicular to one another, and all unequal.

The right rhombic prism. Ends rhombuses. Transverse axes connect centres of opposite lateral edges; they are therefore the diagonals of a rhombus, and so at right angles to each other, but unequal; they are also unequal to the longitudinal axis.

The right rhomboidal prism. Ends rhomboids. Axes connect centres of opposite faces. They are all unequal, and the transverse axes cross one another obliquely.

The right hexagonal prism. Ends regular hexagons. Transverse axes connect either centres of opposite lateral faces, or middle points of opposite lateral edges; they are equal, and form angles of 60° with each other, but are not equal to the longitudinal axis.

1*b*. OBLIQUE PRISMS.—Lateral faces parallelograms; longitudinal axis oblique to plane containing tranverse axes.

Oblique rhombic prism.—Ends rhombuses. Transverse axes connect middle points of lateral edges. They are therefore the diagonals of a rhombus, and are unequal and perpendicular to each other.

Oblique rhomboidal prism.—Ends rhomboids. Transverse axes as in the last. They are therefore the diagonals of a rhomboid, are unequal and cross one another obliquely.

In both these forms the longitudinal axis may be perpendicular to one and oblique to the other of the transverse axes; or it may be oblique to both of them. In the latter case the prism is said to be doubly oblique.

2nd. PYRAMIDAL FORMS.—If we draw straight lines to the angles of a plane figure from any point outside its plane, the solid so enclosed is a pyramid. The plane figure is called the base, the other bounding figures, which are evidently triangles, the faces: the point is called the vertex. If the line connecting the vertex with the centre of the base is perpendicular to the latter, the pyramid is a right pyramid; if not, an oblique pyramid.

The following pyramidal forms occur:—

The regular octohedron.—If we take two pyramids, with equal square bases, and faces equilateral triangles, and place them base to base, we get this solid. The axes connect opposite angles, and are evidently all equal and at right angles to each other.

The square octohedron.—This solid is formed by putting base to base two pyramids, whose bases are equal squares and faces equal isosceles triangles. The axes connect opposite angles; two being the diagonals of a square, are equal and at right angles to one another; the third is at right angles to these two, but not necessarily equal to them.

Two more forms remain to be described.

The rhombic dodecahedron.—A solid bounded by twelve equal rhombuses. The axes connect opposite angles. It is hopeless to attempt to make the student realise the shape of this solid either by description or a plane figure, but he may easily construct a model of it as follows. Let him cut out in stiff paper or cardboard a figure like that in Fig. 4.

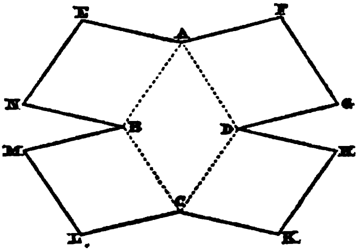

Fig. 4.

Then bend up the four rhombuses *AN*, *BL*, *CH*, and *DF*, round the lines *AB*, *BC*, *CD*, *DA* respectively, till the edges *NB*, *MB* come together, and also the edges *DH*, *DG*, and paste a strip of thin paper over the joining edges to keep them together. He will then have formed one-half the solid, which will stand on the face *ABCD*; the other half may be formed in exactly the same way, placed on the top of the half first formed, and the two joined together by pasting strips of thin paper along the edges. The dodecahedron so formed will have two of its opposite faces open. Now let him pass a thread from *A* and *C* to the opposite angles, and another from the point where *N* and *M* have been brought together to that where *H* and *G* have been brought together. These threads are the axes, and by looking through the open faces, a little geometrical reasoning will show that they are equal and perpendicular to one another.

The rhombohedron.—A solid bounded by eight equal rhombuses. Of this the student had better make a model thus. Cut out the figure in Fig. 5; bend up along the lines *CD*, *EF*, *GH*, till *KL* and *AB* coincide, and fasten the two latter together with a strip of paper and gum. This will give a rhombohedron with two faces open. He will find that the three plane angles, which contain the solid angles at *C* and *G*, are all equal, but that such is not the case with the other solid angles. *C* and *G* are called the vertices, and the edges that meet them are called vertical edges; the other six edges are called lateral edges. Threads connecting the middle points of opposite lateral edges will be the transverse axes; they are easily seen to be the lines connecting the opposite angles of a regular hexagon, and are therefore equal, and inclined at angles of 60° to each other; a thread connecting the two vertices is the longitudinal or principal axis; it is evidently perpendicular to the transverse axes.

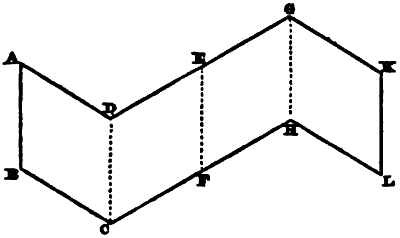

Fig. 5.

It is clear that the rhombohedron is only that particular case of the oblique rhombic prism in which all the edges are equal. One main reason for making it a distinct form, and giving it the above set of axes, is, that optical phenomena show that the principal axis is intimately connected with the molecular structure of the crystal.

Classification of Fundamental Forms.—The fundamental forms just described are classed according to the number, relative dimensions, and inclinations of their axes in the following six systems.

Forms with three axes all perpendicular to one another.

1. Monometric, Isometric, Tesseral, Cubic, or Regular System. Axes all equal.

Cube, Regular Octohedron, Rhombic Dodecahedron.

2. Dimetric, Pyramidal, or Tetragonal System. Only two equal axes.

Right square prism. Square octohedron.

3. Trimetric, Rhombic, Orthorhombic, or Rhombohedral system. Axes all unequal.

Right rectangular prism. Right rhombic prism.

Forms with three axes, not all perpendicular to each other.

4. Monoclinic or Oblique System.

Axes all unequal; two perpendicular to each other, one of these two being perpendicular and the other oblique to the third axis.

Right Rhomboidal Prism. Oblique Rhombic Prism, in which the longitudinal axis is perpendicular to one of the transverse axes.

5. Triclinic or Anorthic System.

Axes all unequal and all oblique to one another.

Doubly-oblique Rhombic Prism. Doubly-oblique Rhomboidal Prism.*

Forms with four axes; three transverse, equal, and making angles of 60° *with one another; longitudinal perpendicular to transverse and not equal to them.*

6. Hexagonal, Rhombohedral, Rhomboidal, or Monotrimetric System.

Hexagonal Prism and Rhombohedron.†

Laws of Crystalline Form.—The following are the two main laws respecting Cleavage and Crystalline Form.

(1.) Cleavage takes place parallel to the faces of a fundamental form, or to the diagonals of a face.

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* For that form of the Oblique Rhomboidal Prism, in which the longitudinal axis is perpendicular to one of the transverse axes, some authors have invented a Diclinic System, in which there are two axes perpendicular to one another, and a third oblique to both these two; but it seems doubtful whether such a form has ever been met with in nature.

† The student will find models a very great aid to understanding the form of crystals. He cannot do better than construct them wholly himself. Full directions will be found in Elementary Crystallography, by J. B. Jordan. Murby, 1873.

(2.) Bodies which have the same chemical composition take, when they crystallise, either the same crystalline shape, or shapes which can be reduced to the same fundamental form.*

The following are the three principal exceptions to the latter law.

1. *Polymorphism.*—Some substances, while retaining the same chemical composition, are capable of assuming crystalline shapes belonging to two or more different systems. This is spoken of as Dimorphism when the different crystalline shapes are two in number; Trimorphism when they are three; and so on.

Sulphur, for instance, crystallises both in octohedral and prismatic forms, and is dimorphic.

2. *Isomorphism or Homœomorphism.*—In some cases two or more bodies, differing in chemical composition, may replace each other in the composition of a mineral, without altering its crystalline form. Such substances are said to be Isomorphous or Homœomorphous with each other.

Thus, for instance, Lime, Magnesia, and Protoxide of Iron are isomorphous substances, which replace one another in many minerals, without producing any alteration in the crystalline shape.

The replacement is well seen in the case of the group of minerals known as Garnets. The chemical composition of all these may be represented by the formula—

$$3(RO)2(SiO_2)+R_2O_3SiO_2,$$

when R in the first bracket is sometimes Calcium, sometimes Iron, sometimes Magnesium.

3. *Pseudomorphism.* — This occurs when a crystal has the crystalline form characteristic of one mineral and the chemical composition of another. For instance, Carbonate of Lime crystallises in rhombohedrons, Quartz in six-sided prisms; we do find, however, crystals of Quartz having the exact shape and angles of a rhombohedron of Carbonate of Lime. Such a crystal is called a Pseudomorph, and in the case mentioned would be described as a Pseudomorph of Quartz after Carbonate of Lime.

Pseudomorphs are arranged in the following classes according to their mode of formation:—

A.—Displacement Pseudomorphs.

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* Very small variations have been noticed in the angles of different crystals of the same substance. These are probably due to the presence of small quantities of mechanically mixed impurities.

(A *a*) *By incrustation*, when one mineral has coated over a crystal of another mineral.

(A *b*) *By replacement*, when the substance of one mineral has been removed, and its place taken by another mineral, the substitution having proceeded atom by atom, so that the crystalline form and sometimes the cleavage of the first mineral is retained.

B.—Alteration Pseudomorphs.

(B *a*). By the removal of constituents.

(B *b*). By the addition of new constituents.

(B *c*). By the taking away of some constituents and their replacement by others.

Thus there are two minerals, Selenite and Anhydrite, each of which occurs in the crystalline form of the other; the first is a hydrated, the second an anhydrous Sulphate of Lime. When we fine Selenite under the form of Anhydrite, one constituent, the water, has been removed, and the case comes under (B *a*). Conversely, Anhydrite in the form of Selenite comes under (B *b*). Again we find Carbonate of Lime with the crystalline form of Selenite. Here the Carbonate of Lime may have been decomposed, and Sulphuric Acid put in the place of Carbonic Acid, and we should then have an instance of (B *c*). But the change may be produced by the gradual removal of the Carbonate of Lime, and, as each atom is taken away, by a corresponding atom of Selenite being put in its place, and then the Pseudomorph would be put in the class (A *b*).

The study of Pseudomorphs, specially those of the last class, often throws great light on the steps through which a rock has passed before it reached its present form. Thus, in many rocks which contain Chlorite, this mineral can be shown not to have been one of the original constituents of the rock, but to have been formed by the alteration of Hornblende or Augite. And thus we learn that certain chloritic rocks, though they now differ from others of Hornblendic composition, may have been originally identical with the latter and formed in the same way.

Forms which are sometimes called Pseudomorphs are also produced in this way. A crystal is removed in solution, and the mould thus formed is afterwards filled up with a non-crystallised substance, and so a cast of the crystal is formed. Thus crystals of Common Salt are sometimes formed by evaporation on the margin of a salt lake; the crystals are afterwards dissolved away, and the hollows produced filled up with mud, and a model of the crystals formed in the latter substance. Mud-casts of the crystals of other salts besides Common Salt have also been noticed, of prismatic crystals of Sulphate of Magnesia for instance (Geol. of Canada, Report to 1863, p. 346).

For details respecting the exceptions noted above, the student must refer to works on Mineralogy.

External Form and Internal Structure of Minerals.—2nd. **Amorphous Forms.**—When minerals have neither external crystalline form nor internal crystalline structure, they are said to be *amorphous.*

Among amorphous forms the following are the most important:—

The Glassy.—At first sight no two things can seem to be so totally distinct as a well-crystallised and a glassy mineral. The regular geometrical form of the one, and the smooth glistening faces along which it breaks, contrast in the most marked way with the shapeless lumps and rough uneven fracture of the other. The same mineral, however, is often capable of assuming both shapes, and experiments lead us to the belief that it is the conditions under which they are formed, that decide whether minerals shall be glassy or crystalline. Thus, if a body harden from a state of fusion, it has been observed in many cases to take the shape of a glass if it cools quickly, and to crystallise if it cools slowly.* And some substances have been found to change slowly from a glass into an imperfectly crystalline mass by a gradual rearrangement of their molecules.

The Colloid, Gelatinous, or Jelly-like.—By certain chemical processes some minerals, Silica for instance, can be precipitated from solution in a gelatinous or jelly-like form. Minerals occur in nature, with very much the look of hardened jelly, which there is good reason to believe were formed by a similar operation.

The Granular, when a mineral consists of grains without external crystalline form. The grains may be rounded, or irregularly angular. Such a structure is often obtained when a substance is precipitated from solution too rapidly to allow of its molecules arranging themselves in crystalline forms. And if minerals are broken up by mechanical force and the fragments in any way bound together again, a granular substance will result. If the fragments are rolled about and rubbed against one another, by running water for instance, the grains become rounded; but if no such action takes place, they are sharp and angular.

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* See, for instance, Sir James Hall's Experiments, Transactions Roy. Soc. of Edinburgh, v. 43.

When substances can exist under two or more physical conditions, they are said to be *Allotropic*. As an instance of Allotropism we may take Carbon, which occurs under the three forms of the Diamond, Graphite, and Charcoal.

Other Properties of Minerals.—There are many other properties of minerals, besides their chemical composition, form, and structure, which are of use in enabling us to recognise them. Of these tests we shall specially notice only those which are of easy application and available in the field.

Streak is the colour of a scratch made on a mineral, or of the mark which it makes on paper or a bit of unglazed porcelain.

The *Colour*, *Lustre*, and *Transparency* are other characteristics it is often useful to note.

The *Hardness* of a mineral is a most useful test. It can be determined either by drawing a knife or file across the mineral, or by seeing what minerals it can scratch and what can scratch it.

Mineralogists have a fixed scale of hardness; the geologist soon learns by use the relative hardness of the few minerals he has to deal with.

Allied qualities are *Fracture*, or the nature of a freshly broken surface, *Frangibility*, and *Toughness*.

The Weight should also be noticed. A rough determination in the hand is sometimes useful in the field.

Some soluble minerals have *Taste*, and others can be made, by rubbing them or breathing upon them, to give off characteristic *Odours*.

The properties of minerals connected with *Light*, *Electricity*, and *Magnetism* cannot be entered into in an elementary treatise, beyond mentioning the fact that, as the field geologist is seldom without a pocket-compass, he has about him the means of finding out whether a mineral is magnetic or not.

The above sketch of the principles of Mineralogy is all we have room for here. The student who wishes to go more fully into the subject may consult Dana's "Manual of Mineralogy," Bristow's "Glossary of Mineralogy;" Nichols's "Elements of Mineralogy," Mitchell's Crystallography in "Orr's Circle of the Sciences," Rutley's "Mineralogy" (Murby's Science Series), Naumann's

"Elemente der Mineralogie," Naumann's "Elemente der theoretischen Krystallographie," and Phillips's "Mineralogy by Brooke and Miller." Perhaps the most complete treatise in English on the subject is Dana's "System of Mineralogy."

SECTION III.—ENUMERATION AND DESCRIPTION OF ROCK-FORMING MINERALS.

We may now pass on to the description of that small body of minerals out of which the great mass of rocks is made up, arranging them, as near as may be, in the order of their relative importance.

A.—Minerals composed of Silica.

The minerals of this class may be divided into two groups according as the Silica that enters into their composition is Anhydrous or Hydrated. The main constituent of the first class is Anhydrous Silica or Silicon Dioxide (SiO_2). Various forms of Hydrated Silica, differing in the amount of water they contain, are known to chemists, the most important being Silicic Acid or Silicic Anhydride $SiO_2,2H_2O$.*

Silicon Dioxide, when crystallised, has a specific gravity of 2·6; it is insoluble in any acid except hydrofluoric acid, and is dissolved under ordinary circumstances only very slowly in boiling solutions of caustic alkali. We can, however, by certain chemical processes,† produce a solution, from which Hydrated Silica may be precipitated in an amorphous or non-crystalline state. We can also, by the method known as dialysis, obtain a solution of pure Silicic Acid in water, and from this Hydrated Silica will separate out in a jelly-like or gelatinous form. Silica obtained by either of these methods has a specific gravity of 2·2 to 2·3. After it has been precipitated, or has gelatinised, it becomes again insoluble, and can be obtained in solution afresh only by repeating the process by which the solution was originally procured.

It should also be noted that Silica, in a nascent state, that is, when just set free from combination, is more readily soluble in acid or alkaline waters than in its ordinary state. In this way, when minerals containing silicates are decomposed by natural causes, a portion of the Silica is taken up and carried away in the water of springs or rivers, and thus the water both of lakes and of the sea holds some Silica in solution. This process is facilitated by an increase of temperature and pressure.

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* Watts's Dictionary of Chemistry and Supplements, Arts. "Silica," "Quartz," and "Opal."

† Roscoe, Lessons in Elementary Chemistry, p. 143; Chemical News, vol. xiii. p. 137.

Quartz.—Anhydrous Silica, pure, or coloured by small quantities of Oxide of Iron and other impurities.

It occurs crystallised in six-sided prisms, terminated by six-sided pyramids, or in double six-sided pyramids, or in modifications of these forms, belonging to the Hexagonal System. No cleavage. Hard enough to scratch glass with ease. Specific gravity when crystallised 2·5 to 2·8. Infusible alone before the blowpipe, with soda fuses to a transparent glass. The crystals known as Bristol, Buxton, or Irish Diamonds are clear transparent Quartz; coloured purple or blue by Oxide of Manganese it forms Amethyst; other coloured varieties have special names.

Quartz, as a constituent of rocks, occasionally occurs in crystals; in most cases, however, it has no external crystalline form, but occurs in rounded glassy grains or "blebs," or in masses of an opaque, milk-white colour; in the latter state it very frequently forms veins, and hence is known as "Vein Quartz." Many rocks also are in a large measure composed of Sand, which is a collection of grains of Quartz worn and rounded by mechanical means.

The great hardness of Quartz, the absence of any cleavage, and its conchoidal fracture, will enable the student readily to distinguish Quartz from any mineral he has much to do with.

Opal.—Hydrated Silica, mixed in the varieties known as Common Opal or Half Opal with Peroxide of Iron, Alumina, Lime, and other impurities. The proportion of water ranges up to 13 per cent. Amorphous conchoidal fracture. Specific gravity 1·9 to 2·3. There is every reason to believe that Opal is hardened gelatinous Silica, produced in rocks by the decomposition of silicates, and separated out by a natural process corresponding to the dialysis by which gelatinous Silica is obtained in the laboratory.

Opal, in its purest form, can be looked upon as only a rare accessory constituent of rocks. An impure Half Opal, however, is deposited from the waters of hot springs—the Geysers of Iceland for instance—in sufficient quantity to form rocks. It also occurs in the form of thin bands or layers in certain siliceous rocks.

Chalcedony, Flint, Chert, Jasper, Agate.—These are the principal examples of a class of minerals which are perhaps Silica in a state of transition from the anhydrous to the hydrated state; according to some authorities they are mixtures of Silicon Dioxide and Silicic Acid, and the soluble portion can be dissolved out by alkaline solutions.*

They occur mainly as nodules or concretions, or in veins, occasionally in thin layers, and form an important ingredient in the constitution of many rocks.

B.—MINERALS COMPOSED MAINLY OF SILICATES.

B (1).—*Felspar Group.*

The Felspars are a group of minerals composed of Silicate of Alumina combined with Silicates of Potash, Soda, and Lime. Small quantities of Magnesia and Oxide of Iron are frequently present.

Their specific gravity ranges from 2·5 to 2·7; and their hardness is 6, that is, they can be scratched by quartz, will scratch glass, and cannot be touched by the knife, or only to a slight degree and with excessive difficulty.

Some of the Felspars are among the most widely distributed of the rock-forming minerals. The principal species are as follows:—

Orthoclase or Potash Felspar.—Composed of one equivalent of Potash, one of Alumina, and six of Silica: $KO, Al_2O_3, 6(SiO_2)$. A small part of the Potash is often replaced by Soda, and a little Lime and Oxide of Iron are often present.

Monoclinic, in modified oblique prisms. *Cleaves*, parallel to the base and to the diagonal, which is oblique to the longitudinal axis of the prisms. The two cleavages are therefore at right angles to one another, whence the name. *Streak*, greyish white. *Lustre*, vitreous, and pearly on the cleavage faces. *Fracture*, conchoidal to uneven and splintery. Not acted on by acids.

Sanidine or Glassy Felspar is a common variety of Orthoclase. The crystals are of a glassy brightness, more or less transparent, and often cracked and creviced.

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* Zirkel, Lehrbuch der Petrographie, vol. i. p. 291.

It is very generally stated that Orthoclase is confined to the older and Sanidine to the newer crystalline rocks; but it is very doubtful whether the latter part at least of this generalisation can be upheld by facts.

Albite or Soda Felspar.—Composed of one equivalent of Soda, one of Alumina, and six of Silica: Na_2O,Al_2O_3, $6(SiO_2)$: generally very small admixture of Potash, Lime, Magnesia, Oxide of Iron.

Triclinic, in modified oblique rhomboidal prisms. Generally occurs in flat twin crystals. *Colour*, mostly white; tinges the blowpipe flame yellow. *Streak*, colourless. *Fracture*, uneven. *Lustre*, vitreous, pearly on basal cleavage planes. Not acted on by acids.

Oligoclase.—Composed of two equivalents of a Protoxide, two of Alumina, and nine of Silica: $2(RO),2(Al_2O_3)$, $9(SiO_2)$.

Soda is the most common Protoxide, but it is often partly replaced by Potash, Lime, or a small admixture of Magnesia. Oxide of Iron is also frequently present in small quantities.

When crystallised, *Triclinic* in doubly oblique rhomboidal prisms. *Cleaves*, parallel to the base and shorter lateral axis. *Streak*, colourless. *Fracture*, conchoidal or uneven. *Lustre*, resinous; on principal cleavage planes vitreous or pearly. Insoluble in acids. May often be distinguished from Orthoclase by the presence of fine parallel striations on the basal cleavage planes.

Labradorite or Lime Felspar.—Composed of one equivalent of a Protoxide, one of Alumina, and three of Silica: $RO,Al_2O_3,3(SiO_2)$.

The Protoxide is mainly Lime with some Soda; there are generally small admixtures of Potash and Magnesia.

Triclinic, in doubly oblique rhomboidal prisms. *Cleavage*, parallel to base, mostly coloured, and sometimes shows a beautiful play of rich tints. *Streak*, colourless, white. Differs from preceding Felspars in being entirely soluble, when powdered, in nitric or heated hydrochloric acid.

Anorthite, another Lime Felspar.—Composed of one equivalent of Lime, one of Alumina, and two of Silica: CaO, $Al_2O_3,2(SiO_2)$.

With the Lime there are small admixtures of Soda, Potash, and Magnesia. Alumina replaced to a small extent by Oxide of Iron.

Triclinic, usual form a doubly oblique rhombic prism.

Cleavage, parallel to the base and shorter lateral axis. *Streak*, colourless, white. *Fracture*, conchoidal. Completely soluble in concentrated hydrochloric acid without gelatinising.

In all the Felspars there is present one equivalent of Protoxide to one equivalent of Alumina, but the proportion of Silica varies. Thus if we represent the Protoxide by p, the Alumina by a, and the Silica by s, we have:—

$p : a : s :: 1 : 1 : 6$ in Orthoclase and Albite.
$:: 1 : 1 : 4\frac{1}{2}$ in Oligoclase.
$:: 1 : 1 : 3$ in Labradorite.
$:: 1 : 1 : 2$ in Anorthite.

The first two Felspars are hence spoken of as Highly Silicated or Acidic; the rest as Poorly Silicated or Basic.

The Felspars are also subdivided according to their crystalline form into Monoclinic or Orthoclastic, and Triclinic or Plagioclastic. The two principal cleavages of a Monoclinic Felspar are inclined to one another at an angle of 90°; the two chief cleavage planes of a Triclinic Felspar inclose an angle less than 90°. Orthoclase is a Monoclinic Felspar, all the rest mentioned above being Triclinic. There is an easy test by which we can frequently detect Triclinic Felspars. When light is allowed to play on the basal cleavage plane, a fine parallel striation is frequently detected; this striation is not found on the basal cleavage planes of Monoclinic Felspars.* Whenever, then, this striation or striping is visible, we may be sure that the Felspar *is not Orthoclase*. We cannot, however, safely infer from the absence of striæ that the Felspar is Triclinic. A Triclinic Felspar will be either Albite or one of the basic forms; and at first sight it does not seem to be a great matter to be able to say this and no more. Practically, however, the chances are, that any Triclinic Felspar which enters largely into the composition of a rock is a basic variety, because Albite rarely occurs as an essential constituent. When, therefore, a rock contains in considerable quantity a Triclinic Felspar, it furnishes a very strong presumption that it is basic and not acidic in composition, and we shall learn by-and-by that this is an important point.

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* See also "Notes on some Peculiarities in the Microscopic *Structure of Felspar*," F. Rutley. Read before the Geological Society, May 12th, 1875.

The foregoing are the best marked and most generally admitted members of the Felspar group of minerals. It will be noticed that the composition of all of them admits of a certain amount of variation; and there are varieties, which we cannot treat of here, which tend to form connecting links between the more pronounced species. In fact, scarcely any two mineralogists are agreed as to how far the different members of the Felspar group are to be looked upon as minerals of fixed chemical composition, and how far as mixtures of definite chemical compounds. The student who wishes to go into this question, will find it noticed in Jukes' "Student's Manual of Geology" (3rd ed. p. 73), and Zirkel's "Lehrbuch der Petrographie" (vol. i. p. 27), and he may further refer to the original memoirs from which those writers have drawn their information. When he comes to know more of the probable way in which the crystalline rocks were formed, he will most likely come to the conclusion that variations in the chemical composition of their constituent minerals is only what might be expected; and that, though it is useful for the purposes of classification, and conduces to clearness of thought, to pick out some of the best defined varieties and give them names, it is necessary to bear in mind that in Nature there are so many connecting links between these more marked forms that no hard line can be drawn between them; and care must be taken not to be led by the love of system into giving to classification more value than it is fairly entitled to bear. The main point for the beginner to bear in mind is the proportion which the Silica of each species bears to the other ingredients, because the acidic and basic varieties keep in a manner apart from one another, and have each a group of associated minerals of their own, and it is upon this circumstance that the main divisions of the crystalline rocks are based.

Two minerals closely allied to the Felspars may be noticed here.

Leucite.—Composed of one equivalent of Potash, one of Alumina, and four of Silica, with admixture of Soda up to six per cent.

Monemetric, in twenty-four faced trapezohedrons. *Hardness*, 5·5 to 6. *Specific Gravity*, 2·4 to 2·5. Soluble in hydrochloric acid.

Nepheline.—Composed of four equivalents of a Protoxide, four of Alumina, and nine of Silica. The Protoxide consists of Soda and Potash, and most analyses give four atoms of Soda to one of Potash. Small variable quantities of Lime and Sesquioxide of Iron are also often present.

Hexagonal, in six-sided tabular crystals or prisms. *Hardness*, 5·5 to 6. *Specific Gravity*, 2·58 to 2·65. Gelatinizes with acids.

We may also notice here a very numerous body of minerals included under the family name of Zeolites.

They are closely related in chemical composition to the Felspars, but differ from them in all containing water, the amount varying from 4 to 22 per cent. It is from this latter circumstance that they derive their name, for the presence of water causes them to froth and bubble up before the blowpipe (ζέω, to boil), it also makes them much more easily fusible than the Felspars.

B (2).—*Mica Group.*

A number of minerals go by the general name of Mica, which all agree in being easily split into thin flakes or leaves.

Their chemical composition is variable, and not very definite; they contain from 35 to 50 per cent. of Silica, 15 to 40 per cent of Alumina, and from 8 to 10 per cent. of Potash; the other ingredients being Soda, Iron, Magnesia, Fluorine, Manganese, Lithia, and occasionally Chromium and the rare metals Cæsium and Rubidium.

Their specific gravity ranges from 2·8 to 3, and their hardness trom 2 to 3; so that sometimes they can be scratched by the nail, and can always be easily scratched with the knife.

The Micas fall into two classes according as they contain Magnesia or not.

(1) *Non-magnesian Micas.*

Muscovite or Potash Mica.—Contains from 45 to 50 per cent. of Silica, 30 to 38 per cent. of Alumina, and about 10 per cent. of Potash, with Iron, Manganese, Fluorine, and occasionally Chromic Oxide; always some water, in some cases up to 5 per cent.

Rhombic, crystals often in six-sided tables. *Cleavage* parallel to base highly perfect. Flexible, and in thin laminæ elastic, the latter property distinguishing it from Talc and Selenite. Not decomposed by acids.

This mineral is found in Russia and elsewhere in plates large enough to allow of its being used for lanterns, windows, and similar purposes; it is then known as Muscovy Glass.

Lepidolite or Lithia Mica.—This mineral differs mainly from the last in containing from 2 to 5 per cent. of Lithia, and a larger percentage of Fluorine, from 2 to 8 per cent. It also contains Soda, and sometimes Cæsium and Rubidium, but no Magnesia, or only very small traces of it. Melts very easily before the blowpipe, colouring the flame red. Imperfectly soluble in acids, wholly so after fusion.

(2) *Magnesian Micas.*

These contain 39 to 41 per cent. of Silica, and Magnesia in varying amounts up to 30 per cent.; they are also richer in Sesquioxide of Iron than the Non-magnesian Micas.

The two chief varieties are known as Biotite and Phlogolite.

The Micas are easily recognised by the ease with which they split into thin flakes, which are both flexible and *elastic.* The only other common minerals which split in the same way are Talc and Selenite, and the laminæ of these are flexible but *not elastic.* Talc also has a greasy feel, which serves to distinguish it.

It is, however, by no means easy to say to which species any particular specimen of Mica belongs, and this can often be determined only by chemical analysis or optical properties. Perhaps as a rule the Magnesian Micas are more generally dark-coloured than the Non-magnesian.

B (3).—*Hornblendic or Augitic Group.*

The minerals of this group are bisilicates of one or more protoxide bases, such as Lime, Magnesia, Protoxide of Iron, and Protoxide of Manganese. The protoxides replace one another isomorphously, and give rise to great variation in the chemical composition of different varieties. Part of the Silica is also frequently replaced by Alumina. In their normal state they contain no water, but certain species have a tendency to take up water, and thus give rise to new varieties.

The two chief species are Hornblende and Augite.

Hornblende or Amphibole.—In these varieties, which contain

Alumina, the proportion varies up to 14 per cent. Silica varies from 45 to 60 per cent.

Monoclinic, in modified forms of an oblique rhombic prism. *Cleavage*, parallel to one face of the prism very perfect, frequently laminated and sometimes fibrous. *Colour*, usually black or greenish black, but also of various shades of grey, yellow, or brown, and even white. *Streak*, white, or paler than the colour. *Hardness*, 5 to 6. *Tough*. *Specific Gravity*, 2·9 to 3·4.

Augite or Pyroxene.—In the aluminous varieties, which are the most plentiful, the Alumina ranges up to 8 per cent. Silica varies from 47 to 56 per cent.

Monoclinic, in modified oblique rhombic prisms. *Colour*, black or greenish black, but sometimes of paler tint. *Streak*, white or greyish. *Hardness*, 5 to 6. *Brittle*. *Specific Gravity*, 3 to 3·5.

In chemical composition Hornblende and Augite are similar, and, indeed, the variations in this respect to which both are liable, are so great that it seems scarcely possible to distinguish between them on this ground, though, perhaps, Augite usually contains more Lime and less Alumina than Hornblende.

Their crystalline forms, however, though both belonging to the same system, differ in their angles, and, when crystals perfect enough to be submitted to measurement can be obtained, the two minerals may be distinguished by this test. Sometimes the difference can be detected by the eye, for the larger angle of the Hornblende prism is 124° 30′, and in Augite varies from 87° 5′ to 92° 55′, the one being sensibly larger than a right angle, and the other as near as may be a right angle. Hornblende also frequently occurs in a laminated form; Augite rarely or never. One of the varieties of Hornblende, Uralite, however, is said to have the external form of Augite and the cleavage of Hornblende.

These facts lead one to the belief that Hornblende and Augite are really only two forms of the same mineral; and that the difference between them is owing to a difference in the physical circumstances under which they were formed, such, for instance, as rate of cooling, if they arose from a state of fusion.

It is however worthy of notice, that, while Hornblende occurs associated with free Quartz and the more highly silicated as well as the basic Felspars, it is said that Augite has never yet been found with Quartz or Orthoclase.

But we are quite ignorant whether this, and many other facts respecting the association of minerals, was true of the rock from the time of its first formation, or whether it is due to subsequent alteration. But this is a subject that must be deferred to a subsequent chapter.

Diallage and *Bronzite* are foliated varieties of Augite. The surface of the thin plates into which they are divided are of a pearly lustre in the first, and brassy and metallic in the second.

Hypersthene is a mineral agreeing with Augite in general composition, but crystallising on the Rhombic System.

Olivine.—Silicate of Magnesia, the Magnesia being frequently replaced in part by Protoxide of Iron; a little Protoxide of Manganese is also frequently present.

This mineral occurs most frequently in glassy masses of an olive green colour in Basalt and other rocks.

B (4).—*Talc and Chlorite Group.*

The minerals which may be placed together under this head are essentially Hydrated Silicates of Magnesia. They are soft, and have usually a soapy or greasy feel. Their specific gravity ranges from 2·5 to 2·8.

Talc.—Hydrated Bisilicate of Magnesia, with from 1 to 4 per cent. of Protoxide of Iron, and Alumina up to 5 per cent. Found rarely in six-sided tables; believed to belong to either the Rhombic or Monoclinic System; usually with a foliated structure, which allows it to be split into thin plates, that are flexible but not elastic. White, silvery white, or greenish, with pearly lustre. Streak, white or paler than the colour. Very soft, and easily cut with a knife. Unctuous to the touch.

Chlorite.—Hydrate Silicate of Magnesia and Alumina with Protoxide of Iron.

Hexagonal, sometimes in tabular six-sided prisms. Oftener granular and disseminated in scales. Very soft. Not so unctuous to the touch as Talc, and yields water when heated in a glass tube, which Talc does not. Usual colour a dark olive green. Streak, greenish gray.

Serpentine.—Hydrated Silicate of Magnesia with small quantities of Alumina and Protoxide of Iron.

Rarely occurs crystallised in doubtful forms. Usually massive. Colour very frequently different shades of green, sometimes red and brown, often veined and mottled. Harder than Talc or Chlorite, but may be easily cut with a knife. Slightly soapy feel.

C.—Compounds of Lime.

One of the most widely diffused and important minerals the geologist has to deal with is Carbonate of Lime. When crystallised it occurs under two forms, one of which, Calcite, is extremely common; the other, Aragonite, is not so frequently met with.

Calcite or Calc Spar.—*Rhombohedral,* primary form an oblique rhombohedron. *Cleavage,* very perfect and easy parallel to all the faces of the rhombohedron.* *Hardness,* 2·5 to 3·5, so that it can be easily scratched with a knife. *Specific Gravity,* 2·6 to 2·7. Effervesces briskly with acids.

The crystals, when sufficiently transparent, are strongly double refracting.

This, which is one of the commonest, is also the most easily recognised of minerals. Its ready and perfect cleavage, the ease with which the knife scratches it, and its effervescence with acids, distinguishing it from any mineral which it otherwise resembles.

Aragonite.—Rhombic. Usually in compound prismatic crystals, the cross section of which is star-shaped with re-entering angles. Also very frequently fibrous, with sometimes a silky lustre. Can be scratched with a knife, but is sensibly harder than Calcite. Effervesces with acids.

Bitterspar.—Composed of Carbonate of Lime and Carbonate of Magnesia. *Rhombohedral.* The primary Rhombohedron differs very slightly from that of Calcite, but the faces are very commonly curved. The lustre of the cleavage planes is also often somewhat pearly. Effervesces much more slowly than Calcite with cold acid, but the powder effervesces briskly with hot acid. Somewhat harder than Calcite. These tests will generally distinguish it from Calcite, which otherwise it much resembles.

The proportions of the two carbonates vary very much in different specimens, as will be seen from the following Table of analyses taken from Dana's Mineralogy †

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* See page 25.

† See also Bischof, Chemical Geology, ii 47.

Atomic proportion of Carbonate of Lime to Carbonate of Magnesia.	Theoretical Composition.		Composition of specimens analyzed.	
	$CaCO_3$	$MgCO_3$	$CaCO_3$	$MgCO_3$
1 : 1	54·35	45·65	51·0 to 57·91	44·32 to 38·97
3 : 2	64·1	35·9	59·0 to 65·21	39·50 to 34·79
2 : 1	70·4	29·6	73·0 to 68·0	25·0 to 25·1
3 : 1 to 5 : 1			77·63 to 85·84	18·77 to 10·39
1 : 3			27·53 to 28	67·97 to 67·4

The first variety in the Table is usually looked upon as the normal type of the mineral, and the others are supposed to be produced by portions of one carbonate being replaced by corresponding portions of the other. The Crystalline forms of the two carbonates differ so little, that we can easily imagine this replacement taking place without the crystalline form of the compound or mixture being affected to any great extent. It is said, however, that the angles of the Rhombohedron of Bitter Spar are not constant, but approach those of Carbonate of Lime or Carbonate of Magnesia, according as the first or second salt predominates in the composition.

This mineral is also sometimes called Dolomite, but it will be convenient to restrict that term to *rocks* in which Bitter Spar is the main ingredient.

Gypsum.—Hydrated Sulphate of Lime. The crystallised form is known as *Selenite*. *Monoclinic*, generally in flat right rhomboidal prisms, often combined so as to give arrow-headed forms. *Cleaves* with ease in one direction, giving thin plates which are flexible, but not elastic. Soft enough to be scratched with the nail. Pure varieties white and semi-transparent, with pearly lustre; frequently stained with various colours.

Gypsum also occurs amorphous in large masses, and in thin layers, or veins, which are frequently fibrous, and have a silky lustre.

Anhydrite.—Anhydrous Sulphate of Lime. *Rhombic*, three cleavages at right angles to one another. About as hard as Calcite.

The two following are not uncommon as accessory minerals:—

Fluor Spar.—Fluoride of Calcium ($CaFl_2$). The crystalline form and cleavage have been described on p. 20. Rather harder than Calcite. Of various colours, and often with a brilliant gemlike lustre. When heated with sulphuric acid gives off hydrofluoric acid, which corrodes glass. Gives a phosphorescent light when placed on heated iron.

Apatite.—Phosphate of Lime ($Ca_3 2PO_4$), with very frequently some Fluoride or Chloride of Calcium. *Hexagonal*, in modified hexagonal prisms. Harder than Fluor Spar, but not so hard as Orthoclase. Dissolves slowly in nitric acid, but without effervescence.

The compounds of Iron, and some few other minerals, which can hardly be considered to belong to the Rock-forming class, have already been noticed (p. 18). There are also other accessory minerals of very common occurrence, which will, sooner or later, come under the student's notice; but for descriptions of these he must turn to works on Mineralogy or larger treatises on Geology.

SECTION IV.—LITHOLOGICAL CLASSIFICATION OF ROCKS.

We have now given a sketch of such parts of Mineralogy as will suffice for the needs of a beginner. The student, when he has mastered this, may be compared to a child that has learned its alphabet; and as the next step with the child is to show him how letters are put together to form words, so we must now go on to show the reader how the minerals, with which he has made acquaintance, are combined into rocks.

Lithological Classification of Rocks.—We will first see what results would be arrived at by Lithology, or an indoor examination of hand-specimens alone. By this method of research one would be led to divide rocks into two great classes—Crystalline and Non-crystalline or Granular.

Crystalline Rocks.—The rocks of the first class consist of crystals with their angles and edges sharp and unrounded, embedded in a paste not so distinctly crystalline.

Non-crystalline Rocks.—The Non-crystalline or Granular rocks, on the other hand, are composed of particles more or less rounded, worn, or broken, held together by a cement or paste. The latter may be crystalline, but the student must not imagine the possession of a crystalline cement in a Non-crystalline rock in any way allies it to the rocks of the first class. Why this is, we cannot explain at present; but we shall see by-and-by that the modes of formation of the two kinds of rock were totally different.

To these main subdivisions the lithologist would probably add two more, either as independent or subordinate classes.

One would include certain rocks closely resembling in many respects members of the Granular class, which yet show a marked tendency towards a crystalline texture; rocks which give the idea that they have been once identical with the Granular rocks they still resemble, but have had a certain amount of crystallisation superadded to their original condition.

The second additional class would take in rocks which may be separated on these grounds. While in many of the Crystalline rocks the constituent minerals are thrown together without order or arrangement, in these rocks there is a tendency for the different minerals to be arranged each one by itself, in separate layers. Such rocks go by the name of Schistose (σχιστός, split), or Foliated (Folium, a leaf), because the arrangement of their components tend to make them split into thin flakes or leaves.

Lithological examination, then, leads us to the following classification of rocks:—

1. Crystalline.	1 *a*. Confusedly crystalline: minerals not arranged in any order.
	1 *b*. Schistose or Foliated: minerals arranged each by themselves in separate layers.
2. Non-crystalline or Granular.	2 *a*. With no trace of crystallization, unless it be a crystalline cement.
	2 *b*. With more or less of a tendency to a superadded crystalline texture.

Some rocks would still remain, which it would puzzle a lithologist to assign to their proper place in the above scheme. He would find all kinds of intermediate steps between the Confusedly Crystalline and the Schistose; and some rocks, such as common roofing slate, which, though undoubtedly granular in texture, are so thoroughly schistose as to seem to require a special class for themselves.

But these imperfections in the classification are only a necessary consequence of the one-sided method by which it was arrived at. It looked merely at the composition and texture of rocks, and paid no heed to the way in which they have been formed. It is only when both circumstances have been taken into account that we can arrive at anything like a satisfactory rock classification.

Some writers would add as distinct classes of rocks the two following:—*

Glassy or Hyaline.—We have already seen that in the case of minerals there was no essential difference between their glassy and crystalline forms, and that it is the condition under which the mineral is formed that determines which shape it takes. The same is equally true of rocks. When we come to describe the different kinds of rocks, we shall find the following two facts to be true. For every glassy rock there is a rock of exactly identical chemical composition with a crystalline texture; and the two forms pass by insensible gradations into one another. And when we come to inquire into the way rocks were formed, we shall see that it was either the rate of cooling, or the degree of fluidity, or some such condition, which caused the rock to assume at one time a glassy and at another a crystalline shape. We may therefore look upon the glassy state as a particular case of the crystalline.

Porodinous, or those which have solidified from a gelatinous state. Certain minerals, such as Opal, we have seen, have in all likelihood been formed in this way, and in some cases considerable bodies of rock have probably been permeated by fluids, from which minerals have gelatinised out and become incorporated with the rock; but it seems very doubtful whether any large rock mass is known, which was ever entirely composed of a gelatinous mineral.

SECTION V.—CRYSTALLINE ROCKS.

In accordance with the classification just given, we will consider first the Crystalline rocks, and will begin with those peculiarities which come under the head of Texture or Grain, and depend on the relative size of the particles.

Texture of Crystalline Rocks.—In some of these rocks the crystals are large enough to be seen by the un-aided eye; such are called *Macro-crystalline*, or *Coarsely Crystalline*. Rocks of this character, when single detached crystals are disseminated in an earthy or less crystalline paste, are said to be *Porphyritic*. In the case of other rocks closer scrutiny or the aid of a pocket lens becomes necessary to enable us to recognise their crystals, and these are known as the *Micro-crystalline*, or *Finely Crystalline*. Lastly, there are the *Crypto* or *Obscurely Crystalline* members, in which crystals can be detected only in highly magnified transparent slices, and by the aid of optical properties, such as polarisation and double refraction.

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* Naumann, Lehrbuch der Geognosie, i. 393.

Some rocks, which cannot strictly be called crystalline, have a *glassy* texture; these are placed in the present subdivision for reasons given a little way back.

Crystalline rocks occasionally put on a loose friable form, and are then said to be *earthy*.

Structure.—We may next pass to the various shapes or structures which Crystalline rocks assume. Some of these can be detected only by the examination of large masses in the field, and belong to the head of Petrology. The following are recognisable in hand-specimens, and may be noticed here.

Rocks full of little rounded cavities, like those produced by the boiling up of gas in a furnace slag, are called *Vesicular*. When the cavities are numerous, the rock is said to be *Scoriaceous* or *Slaglike*, and in the extreme case, when the hollow spaces occupy the major part of the body of the rock, to be *Pumiceous*. We shall see presently that many of the Crystalline rocks have been produced, just like slag, by the cooling of melted matter that flowed out in a fused condition; in these the vesicles are dragged out and elongated in the direction of the flow; in other cases, when the pressure was more nearly uniform in all directions during consolidation, the cavities approach more nearly a spherical shape.

The cavities of a vesicular rock are sometimes filled up with mineral matter; the rock then is called an *Amygdaloid*, from the resemblance of the contents of the hollows to almonds.

Subdivisions of the Crystalline Rocks.—The classification of the Crystalline rocks is a matter of the greatest difficulty. The variations in their composition are all but endless, and present so many intermediate steps from one form to another, that it is scarcely ever possible to establish any two subdivisions between which connecting links may not be found. The anxiety of some observers to elevate every variety that may have come under their notice to the rank of a distinct species, has led to an unnecessary multiplication of names; and more confusion is introduced by different writers using the same name for rocks of different mineral composition.* Still, if we shake ourselves clear of minute details and take a broad view of the composition of this class of rocks, it seems possible to parcel them out into two main subdivisions, sufficiently marked in their mineral composition to be clearly distinguishable from each other, and a third class partaking in some measure of the distinguishing characteristics of the first two. The existence of this third class of course makes it impossible to draw any hard lines between the three classes, and in some cases leaves it doubtful to which of two subdivisions a particular rock ought to be referred; but if we neglect for an instant these connecting forms, and fix our attention on typical instances of the two first-named subdivisions, we shall find these so distinct from each other, and find also among the different varieties of rocks so many that conform more or less closely in mineral and chemical composition to one or other of them, that we may usefully group together the rocks that resemble one type in one class, and those that resemble the other type in a second class, even though we know that between these two classes there lies a debatable ground, into which each of them merges by almost insensible gradations.†

All the Crystalline rocks have a Felspar for one of their principal ingredients, and as the Felspars are divided into the Highly Silicated or Acidic and the Poorly Silicated or Basic, so the Crystalline rocks can be divided into two great subdivisions, according as their prevailing Felspar belongs to the first or second of the Felspar families. The third subdivision mentioned partakes in some degree of the characters of both of the two first.

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* Fortunately these matters are not as important as might at first sight appear. What the geologist wants are not the minute differences insisted on by mineralogists and petrographers, but some broad leading groups in which to arrange the rocks he meets with in the field; and, above all, a careful account of those larger structures which enable him to reason about their origin.

† For a very striking instance of a gradual passage from the extreme type of one of these classes to the extreme type of the other, see Leonhard's Jahrbuch (1873), p. 225.

Acidic Rocks.—The first of these great subdivisions is known as the Acidic, Highly Silicated, Felspathic, or Trachytic class. The Felspar is one of the highly silicated species, Orthoclase or Albite, though Oligoclase is frequently present as well; there is generally also a portion of free or uncombined Silica present in the shape of Quartz. Other minerals may enter into the composition of rocks of this class; but its two distinguishing characteristics are those just mentioned, the highly silicated character of its Felspar and the presence of free Quartz.

The Acidic rocks are poor in Lime, Magnesia, and Iron, and the absence of these substances, which act as fluxes, and their richness in Silica, makes them difficult of fusion. Their specific gravity ranges from 2·3 to 2·7.

Basic Rocks.—The second great subdivision is known as the Basic, Poorly Silicated, Magnesian, Hornblendic, Pyroxenic, Basaltic, or Dioritic class.

The Felspar may be Oligoclase, but is more frequently Labradorite, Anorthite, or some basic form, and Hornblende or Augite is very generally an important ingredient. No free Silica is present as a constituent mineral, but Quartz may occur as an accessory.

Compared with the former class these rocks are poor in Silica, and rich in Lime, Magnesia, and Iron. Hence they are the more readily fusible of the two classes. Their specific gravity ranges from 2·7 to 3·1, so that they are also the heavier of the two.

The extreme and typical rocks of the Acidic and Basic classes are widely removed and clearly distinguishable from each other; as has been mentioned however there are many rocks of an intermediate character which form connecting links between the two, and for the reception of some of these an intermediate class may be established, though it is altogether impossible to say exactly where its boundaries on either side are to be drawn. Perhaps, however, the following may be taken as the broad distinguishing characteristics of each class.

A.—Acidic Class.

Composed of highly silicated Felspar with Quartz.

Relatively light and infusible as compared with the Basic rocks.

B.—INTERMEDIATE CLASS.

Composed of highly silicated Felspar without Quartz.

C.—BASIC CLASS.

Composed of poorly silicated Felspar with Hornblende or Augite. No free Quartz. Relatively heavy and fusible compared with the Acidic rocks.

A very useful rough-and-ready test for determining to which class a crystalline rock is to be referred is furnished by the crust formed on the outside by the action of the weather. The weathered surface of an Acidic rock is very usually white owing to the decomposition of its Orthoclase; the large proportion of iron in the Basic rocks by its oxidation generally stains their weathered crust, often to a considerable depth, brown or red. They also frequently effervesce with acids in the cracks and crevices of the surface, owing to the formation of Carbonate of Lime out of the constituents of their Lime Felspars. These tests are not infallible, but in a majority of cases they may be relied upon.

In the following table the average composition and specific gravity of the rocks of each class is given.

	Specific Grav.	Silica.	Alumina.	Potash and Soda.	Lime & Magnesia.	Oxides of Iron & Manganese.	Water, &c.
Acidic Rocks	2·5	74	12	7	2	3	2
Intermediate Rocks.	2·4	58	17	8	8	7	2
Basic Rocks	2·9	49	17	4	15	13	2

It is easy to see to a certain extent how these subdivisions arose, and why the component minerals of the crystalline rocks do not occur indiscriminately, but are associated together according to broad general laws.

In some cases there has been Silica enough to form the most highly silicated compounds possible, and some to spare besides; in these accordingly the highly silicated Felspars prevail, and the superfluous Silica appears as Quartz; in other cases the Silica was not so plentiful, there was only enough to form poorly silicated compounds, and all there was was used up in doing this; here therefore we find basic Felspars and no free Quartz. Why magnesian silicates should be so much more largely associated with basic than with acidic Felspars is not so easy to explain: the student may consult Durocher's speculations on this point, which he will find very carefully and lucidly explained in Prof. Haughton's "Manual of Geology," chap. i. Appendix A. We must warn him, however, that some of the brilliant Frenchman's facts are, to say the least, doubtful, and others are capable of a very different explanation from that he puts on them.

The scheme of classification just described depends, it will be seen, mainly on the proportion of Silica in each variety of rock. Other authors have subdivided the crystalline rocks according to the Felspar which predominates in them. These, and other like systems, rest on a purely mineralogical basis, and it will be found that they all alike lead, when we come to details, to more or less vagueness of definition and confusion of nomenclature.

To a certain degree possibly this must always be the case. The composition of a large rock mass varies in many cases so much from point to point, that, if we trust merely to mineral composition, it is impossible to fix on a name that will be applicable to all parts of it, and yet there may be satisfactory geological evidence that all the varieties were produced at the same time and fundamentally by the same operation, and that their differences must therefore be from a geological standpoint accidental. Hence arises a constant clashing between mineralogical and geological classification; as yet we have only the first, but the time may come when an arrangement of the rocks now under consideration on a true geological basis will be possible, and then we may hope that many of the present seeming contradictions will vanish. The right thing seems to be to look upon all the present schemes of classification of the crystalline rocks as probably artificial, something like the Linnæan system in Botany, and to wait patiently till a more extended knowledge enables some one, who shall be at once a great petrographer and a great geologist, to establish a natural system, which shall pay regard first and foremost to the method of formation of the rocks, and look upon their mineral composition as merely subsidiary.

One instance will perhaps make these remarks more intelligible. Of the large class of Acidic rocks grouped together as Felstones, some have been lava streams poured out in the open air, some have consolidated from a fused state at great depths below the surface, and some are rocks originally non-crystalline that have been rendered crystalline by heat; of the differences between these three kinds of Felstone a mineralogical classification takes no note, so long as they agree, which they often do, in mineral composition; whereas a natural system would at once place them in distinct and widely separated classes.

We will now pass to some of the more prominent examples of the three classes of crystalline rocks.

A.—Acidic Rocks.

According to the nomenclature now in use the rocks of this class may be grouped under three heads, *Quartzose Trachytes*, *Felstones*, and *Granites*. All are essentially mixtures of Quartz and Orthoclase; Oligoclase is also frequently present to a considerable amount; some of the members contain besides Mica and Hornblende, sometimes as accessories, sometimes in sufficient quantity to make these minerals essential constituents.*

Each of the three families into which we have divided the Acidic rocks contains varieties distinguished either by difference of texture or structure or by slight variations in mineral composition. The last consist mainly in the addition of certain accessory minerals to the normal constituents of the rock, and have not yet been shown to be of geological value. But we have already hinted, and shall show more fully further on, that the texture of a crystalline rock is a matter of the utmost importance, because it indicates the conditions under which the rock was formed. It is therefore on differences in texture and structure that we shall lay especial stress.

To take one instance. In the case of the Trachytes we have the following variations depending on texture or grain:—

Porphyritic Trachyte.
Macro-crystalline Trachyte.
Micro-crystalline Trachyte.
Crypto-crystalline Trachyte or *Rhyolite*.
Glassy Trachyte or *Obsidian*.

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* **For Analyses of the Acidic Rocks, see the table on page 49.**

Other varieties depending on structure are—

Vesicular Trachyte or *Millstone Porphyry.*
Pumiceous Trachyte or *Pumice.*
Concretionary Trachyte or *Perlite.*
Laminated Trachyte or *Phonolite.*

Now some of these varieties are, as far as external characters go, so utterly unlike one another, that lithologically they are separate rock species and have received distinct names. Obsidian is glass, Rhyolite a compact flinty stone, Millstone Porphyry a rough cavernous rock, and no one would suspect from the look of these three rocks that they had anything in common. But, for all that, they, and the other varieties named, are really only the same rock under different forms. They agree in ultimate chemical composition and are made up of the same minerals, and each form can be observed to pass into the one next to it by insensible gradations. And when we come to pass from mere lithological classification to an inquiry into the way in which these rocks were formed, we shall find that the origin of the different varieties was this. All are rocks which were once in a melted state; where the fused mass was cooled quickly, it took the form of a glass or Obsidian; where the cooling was somewhat slower but yet not slow enough to allow of the formation of crystals of any size, a compact rock, Rhyolite, was the result; and as the rate of cooling became less rapid, the rock became more obviously crystalline, and the more coarsely grained varieties were produced. It is very convenient to distinguish these different forms by different names; but the student, when he uses these names, must carefully keep before his mind that the rocks denoted by them are in spite of differences of condition all Trachytes. He may talk of Obsidian, but he must always think of it as Glassy Trachyte.

In the case of some crystalline rocks we have a perfect series from the glassy to the most coarsely crystalline form; in others the series is not complete, some terms having not been observed to occur.

A *a.—Quartzose Trachytes.*

The more coarsely crystalline of these rocks consist of crystals of Sanidine and less abundantly of Oligoclase, with crystals and grains of Quartz, embedded in a paste. Mica, and more rarely Hornblende, occur in them occasionally.

The paste is an intimate mixture of Orthoclase and Quartz, and is often rough and cellular. The grain varies through all degrees of coarseness; sometimes the crystals are numerous and large enough to make the rock porphyritic, and from this form all gradations may be met with down to a rock which may be called micro-crystalline. Where the matrix is open and cellular, the rock yields millstones, and has been called *Millstone Porphyry*.

By a gradual decrease in the coarseness of the grain we pass to the compact or crypto-crystalline form of Trachyte, which has been called *Rhyolite*. This rock is compact, flinty, and sometimes half-glassy; it is composed of Quartz and Orthoclase so intimately mixed, that no grains or crystals can be detected except in highly magnified transparent slices. It is occasionally rendered porphyritic by the presence of crystals of Sanidine, Oligoclase, Mica, and Quartz.

The glassy form of Trachyte is called *Obsidian*. This rock has the appearance and lustre of glass, with a conchoidal fracture, and is usually of a black or dark brown colour. It has sometimes the look of a true homogeneous glass, though even in this case the microscope shows very minute crystals in it; sometimes it becomes porphyritic by the presence of small visible crystals in its glassy matrix; and sometimes it has a vesicular or blistered structure.

The next form we have to notice is *Pumice*, a rough glassy rock, traversed in every direction by cracks and cavities, and made up to a large extent of connected, thread-like masses. It is the hardened froth or foam, that formed on the surface of the seething mass of Trachyte in a state of fusion.

The two most important varieties depending on structure are the Globular and the Laminated forms. In the first the rock is made up of balls or nodules, often consisting of concentric coats like an onion, and made up of fibres radiating from the centre. In the second the rock has a platy structure, so that it may be split into slabs.

A *b.—Felstones.*

The average composition of Felstone is the same as that of Trachyte, only the principal Felspar is the common Orthoclase instead of the glassy variety of that mineral (Sanidine).

The glassy form of Felstone is known as *Pitchstone* or *Retinite*. This is a compact resinous or half-glassy rock, with a strong resemblance to solid pitch, and an imperfectly conchoidal fracture. Except that it contains a larger percentage of water it agrees closely in composition with Felstone in some cases and Trachyte in others, and there can be little doubt that it is the glassy form of a Felsitic or Trachytic rock. It therefore corresponds to Obsidian. As in the case of Obsidian, microscopic examination shows that even the most glass-like forms of the rock are full of minute needle-shaped crystals.

Like Obsidian, Pitchstone becomes occasionally porphyritic by the presence in the glassy matrix of crystals or crystalline grains of Felspar, grains of Quartz, and sometimes plates of Mica.

Compact or crypto-crystalline Felstone is known as *Felsite rock*, *Petrosilex*, or *Eurite;* it is a hard, compact, flinty-looking rock, homogeneous in texture, with a splintery or sometimes imperfectly conchoidal fracture. The most compact varieties resemble very closely Flint or Hornstone, and hence the name Petrosilex was given to it, under the idea that it was composed mainly of Quartz; it is, however, really an intimate mixture of Silica and Orthoclase.

The term *Felsite* is usually confined to aggregates of Quartz and Felspar of so close and compact a texture, that no crystals or grains can be detected on a fresh fracture, and whose composition can be ascertained only by microscopic examination and chemical analysis. This is one extreme form of Felsite rock; varieties, however, often occur which become imperfectly porphyritic by the appearance of separate crystals of Quartz and Felspar in a felsitic matrix.

By gradations of this sort, and the gradual increase in number of the contained crystals, we pass on to the next important variety, *Porphyritic Felstone*, the Felsite Porphyry of the Germans.*

The paste of this rock is identical with Felsite rock itself, consisting of an intimate, compact mixture of

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* The first of these terms seems preferable to the second for the following reasons. The essential fact about the rock is that it is a Felstone, the porphyritic arrangement of its constituents is merely a subsidiary accident, and the accidental character should be denoted by an adjective. Thus we do not call a very tall person a Human Giant, but a Gigantic Man.

Orthoclase, or Orthoclase and Oligoclase, with Quartz; embedded in the paste are crystals or crystalline grains of Quartz and Orthoclase, and in some varieties of Sanidine, Oligoclase, and occasionally Mica.

When the matrix is excessively felsitic with a splintery fracture, and hard enough to strike fire with steel and to be scratched only with difficulty by rock crystal, the rock is called *Porphyritic Hornstone*. A variety, whose matrix has a dull and uneven fracture and is more evidently crystalline than the last, is the typical *Porphyritic Felstone*. When the matrix is dull and earthy, the rock is known as *Porphyritic Claystone:* this form is probably the result of decomposition. In most Felstone the Quartz is so intimately mixed up with the Felspar as not to be separately recognisable by the eye, and where it is separated out it usually occurs in rounded lumps; one variety, however, contains *crystals* of Quartz embedded in a felsitic paste. This rock is sometimes called by the objectionable name of *Quartz Porphyry;* perhaps *Elvanite* might be used to distinguish it.

The majority of the Felstones are compact rocks, but occasionally they show a porous and vesicular texture; such occur in the Thuringerwald and elsewhere, and are worked for millstones, whence their name "millstone-porphyry." It does not seem to be satisfactorily made out whether the peculiar texture of these rocks is original, or whether it is due to decomposition; if the first is the case, they would take the same place among the Felstones that Pumice occupies among the Trachytes.

Felstones also occur with a globular concretionary structure, corresponding in some degree with the similar varieties of Trachyte.

Schistose Felstones, splitting into slabs, are also met with, and may be analogous to the laminated form of Trachyte. It is somewhat doubtful in many cases how far this structure is original and how far it is due to a rearrangement of the particles of the rock after its formation, by which it had a tendency given to it to split into slabs. We shall see by-and-by that many rocks have had this structure, which is known as cleavage, set up in them by being subjected to great pressure.

Some schistose Felstones are undoubtedly cleaved, but in the case of some of the corresponding Trachytic forms it seems so impossible that they can have been subjected to the pressure necessary to produce cleavage that we must look on these platy structures as original.*

A *c.*—*Granites.*

The Granite group includes two principal varieties, Granite proper and Syenitic or Hornblendic Granite.

Granite.—A coarse crystalline mixture of Felspar, Quartz, and Mica. The Felspar and Quartz are mingled into an aggregate, through which the Mica is strewn about without any order or arrangement.

The Felspar is often all Orthoclase, but many Granites contain Oligoclase as well; the latter, however, is never found alone. In the Granite of the Mourne Mountains in Ireland, Professor Haughton found Albite "incrusting the interstices of the Orthoclase and Quartz in the cavities of the rock," and "in the body of the rock itself in small quantities." †

The Quartz rarely occurs crystallised; usually as glassy lumps, which fill up the spaces between the other minerals, and are sometimes seen to have moulded themselves on the latter.

The Mica is more usually the white Potash Mica than the dark Magnesian Mica.

The grain of Granite shows every degree of variety, from close and compact up to excessive coarseness. The more finely-grained varieties occur most plentifully in veins or on the edges of large masses; in such cases we frequently find the Granite to become gradually finer and finer in grain, and to lose its Mica by degrees, till at last it passes first into Elvanite, and then by insensible gradation into a rock indistinguishable from compact Felstone.

The large-grained Granites usually owe their coarseness to the presence of large crystals of Orthoclase; sometimes the latter contrast so strongly in size with the other materials as to give the rock a porphyritic aspect. In the variety known as Graphic Granite the Orthoclase and

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* The rock called Halleflinta and some other schistose felspathic rocks, which are usually put among the Felstones, seem to be unquestionably altered rocks, and must be placed among the rocks hereafter to be described as Metamorphic.

† Quart. Journ. Geol. Soc. of London, xii. 190; Geological Magazine, vi. 561.

Quartz are arranged somewhat in alternate plates, and the latter penetrates the former in such a way that a section perpendicular to the lamina shows figures which have been compared to Hebrew characters.

Variation in the proportion of the constituents and the presence of accidental minerals give rise to numerous varieties of Granites, which petrologists have honoured with distinct names; all the principal varieties, however, pass into one another, and none of them seem entitled to the distinction of being considered well-marked rock species.

Syenitic Granite.—If the Mica of Granite is accompanied or replaced by Hornblende, the rock, according to the nomenclature in use in England, is called Syenite. The German petrographers, however, usually call such a rock Syenitic or Hornblendic Granite, and define Syenite to be a crystalline compound of Orthoclase and Hornblende. It seems, however, that there are numerous connecting links, caused by the gradual disappearance of the Quartz and Mica, between Hornblendic Granite and the Syenite of the Germans.

Chemical and Mineral identity of Acidic Rocks.—The description given of the chief varieties of Trachyte and Felstone point to a strong resemblance in mineral composition and in petrological structure between these two rocks. The analyses given below confirm this idea, and all the facts lead to the belief that the two are in all essential particulars one and the same rock, and that any differences that do exist between them are due either to the conditions under which they were formed or to changes that have been impressed upon them since their formation. Granite again differs from these two rocks mainly in two respects: first, it contains a considerable proportion of Mica, a mineral which is, however, occasionally present in both of them; secondly, in Granite the Quartz usually occurs in masses large enough to be easily recognised, while in most of the Felstones and Trachytes it is so intimately mixed up with the Felspar of the paste as not to be detected by mere inspection; some of the Quartz Trachytes, however, and the variety of Felstone which has been distinguished as Elvanite, approach Granite in the distribution of their Quartz.

Textural Varieties pass into one another.—We may say then, that, as far as mineral and chemical composition go, all the members of the Acidic class of Crystalline rocks are almost identically the same, the variations which they show in these two respects being confined within very narrow limits; and it is mainly on the score of texture that the several species are separated from one another and receive different names. And in this respect it is instructive to note how the different forms can be arranged in a series, such as is given in a tabular form below, which shows the most complete and gradual passage from one extreme to the other. At one end stand the coarsely-grained Granites and some of the rougher forms of Quartz Trachyte; a little finer than these are Elvanite, Porphyritic Felstone, and ordinary Quartz Trachyte; these last, as the grain becomes by degrees smaller and smaller, pass insensibly into the flinty Felsites and Rhyolites; at last, by going still in the same direction, we reach the perfect glass of Pitchstone and Obsidian. And this is no mere fanciful arrangement, it is the very order in which rocks of this class are often found to occur in nature. The outside of a body of crystalline rock often consists of a wall of Pitchstone; further in the mass the rock gradually merges into Felsite; and this, as we get well into the heart of the mass, becomes more distinctly crystalline till it passes into one of the coarsely-grained forms.

The fact just stated is so full of meaning that we have thought it well to place it here before the reader, though by good rights it belongs to a more advanced stage of Geology than Lithology, and we will further anticipate by pointing out its meaning. We shall learn by-and-by that the crystalline mass was once thrust in a melted state through the rocks which surround it; the outside portions, which touched the cold rocks on either side, cooled fastest and assumed a glassy form; then comes a space where the cooling was slower, but yet not slow enough to allow of the formation of distinct crystals; in the interior, from which the heat escaped very slowly, there was time enough, before the mass cooled, to allow of the formation of large and numerous crystals, and the rock put on a coarsely-grained crystalline texture.

That the above explanation is true in many cases there can be little doubt: in other cases, however, it is possible that the molten mass contained, when it was poured out, crystals previously formed in it, or derived from the adjoining rocks.*

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* Scrope, Volcanoes, pp. 116, 117.

Table showing the Passage from the Glassy into the Coarsely Crystalline Forms of the Acidic Rocks.

	Quartzose Trachytes.	Felstones.
Glassy Form	*Obsidian.*	*Retinite.*
Compact Form	*Rhyolite.*	*Felsite.*
Crystalline Forms	*Granular and Porphyritic Trachyte.*	*Granular and Porphyritic Felstone.*
Coarsely Crystalline Forms.	*Elvanite.* *Hornblendic Granite.* *Granite.*	

B.—Intermediate Rocks.

Of the endless varieties of rocks that may be placed under this head the following have been selected as the commonest and most typical.

Quartzless Trachytes.—These rocks consist of Sanidine, with or without Oligoclase, embedded in a rough porous felspathic paste, usually of a dull white or pale grey colour, but occasionally showing darker tints. The chief varieties of the Quartzless Trachytes have been distinguished, according to the nature of their prevailing mineral, as Sanidine-Trachyte, Oligoclase-Trachyte, and Sanidine-Oligoclase-Trachyte.

Andesite is a name given to a Trachytic rock in the Andes. The descriptions given by different petrologists of it are very conflicting,* but it seems to be mainly an Oligoclase Trachyte, with a composition very closely approaching that of the Sanidine-Oligoclase variety, though it is doubtful whether Sanidine occurs in it. Zirkel makes four varieties: Hornblende-Andesite with Quartz, Quartzless Hornblende-

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* See Cotta, Rocks Classified and Described (English Translation), p. 191. Such discrepancies as those described in the passage referred to, between the descriptions given by authors of undoubted ability and trustworthiness of the mineral composition of the same rock, are at first not a little disheartening. But they will not seem so startling, if we reflect that no large body of rock has anything like a uniform composition, and that the examination of hand-specimens taken from spots some way apart may give results widely differing from each other.

Andesite, Augite-Andesite with Quartz, and Quartzless Augite Andesite. The varieties containing Quartz, however, seem to have a lower percentage of that mineral than the Quartz Trachytes.

Domite is an earthy, friable rock, found in the district of the Puy de Dome in Central France, probably an altered Oligoclase Trachyte.

There are two varieties of the Trachytes which have received distinct names on account of their structural peculiarities.

Pearlstone or *Perlite* is a concretionary form, in which the rock is made up of irregular balls or spheres, often with a concentric and radiated structure. The texture is often imperfectly glassy, which gives the surface of the spheroids a pearly lustre, whence the name.

Clinkstone or *Phonolite* has a scaly or slaty structure, so much so at times that it can be split into slabs for roofing. It is somewhat poorer in Silica than the generality of the Trachytes, but it is geologically connected with Trachyte. It will be recollected that forms analogous to these two occur among the Quartzose Trachytes and the Felstones.

Some of the Obsidians and Pumices are the glassy and frothy forms of Quartzless Trachytes.

Minette.—This rock is composed of an abundance of Magnesian Mica in a felspathic paste, whose composition resembles very closely that of Orthoclase. Plates of Orthoclase may be occasionally detected, and very rarely grains of Quartz.

The Mica is very plentiful, quite equal in quantity to the paste usually; sometimes this mineral is so abundant that the rock seems altogether made up of it. The distinguishing character of this rock seems to be its large proportion of Mica, which distinguishes it from Micaceous Syenite and other rocks composed of Orthoclase and Mica.

Syenite (of the Germans).—This rock is defined to be a coarsely crystalline mixture of Orthoclase and Hornblende; it contains also a triclinic Felspar (Oligoclase according to G. Rose) very often, Mica frequently, and occasionally some Quartz.

The only difference between Syenite and the Hornblendic form of Granite seems to be that the former contains very much less Quartz than the latter; in fact, in order to entitle a rock to the name of Syenite this mineral ought to occur in such small quantity as to be no more than accessory. Syenite is an admirable instance of the way in which rocks of the intermediate class form connecting links between those of the Acidic and Basic subdivisions. Cases have been noticed, on the one hand, where the Quartz gradually increases, and the rock passes into an Hornblendic Granite; and, on the other hand, the Orthoclase has been found to disappear by degrees, and the rock to shade off into a Diorite.

Closely allied to Syenite is a rock which has been called *Syenite Porphyry* by G. Rose, and *Quartzless Orthoclase Porphyry* by Zirkel. The two differ mainly in texture, Syenite being crystalline throughout, while Syenite Porphyry is, as its name implies, more or less porphyritic, and consists of crystals of Orthoclase, Oligoclase, Hornblende, and Magnesian Mica, embedded in an orthoclastic paste. It would probably be safe to look upon this rock as a variety of Syenite, and call it Porphyritic Syenite.

C.—Basic Rocks.

The rocks of this class may be grouped under the following heads:—

C *a.—Diorites.*

Oligoclase and Hornblende.

Compact form. *Aphanite.*
Crystalline form. *Common Diorite* and *Porphyrite.*

C *b.—Melaphyres.*

Oligoclase and Augite.*

C *c.—Basalts.*

Labradorite and Augite.

Glassy form. *Tachylite.*
Compact form. *Common Basalt.*
Finely crystalline form. *Anamesite.*
Coarsely crystalline forms. *Dolerite, Hypersthene Rock, Gabbro.*
Altered (?) form. *Diabase.*

C *d.—Corsite.*

Anorthite and Augite or Hornblende.

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* Under the head of Augite we include here, besides common Augite, certain other augitic minerals, such as Diallage.

C *a.—Diorites.*

The rocks that come under this head are essentially mixtures of Oligoclase and Hornblende. The Hornblende may be replaced by Mica, generally Magnesian Mica. Quartz is sometimes present, but the Quartzless and Quartzose forms pass into one another by insensible gradations, so that geologically no line of separation can be drawn between them.

The Diorites may be grouped according to their texture under three heads:—

Compact Diorite or Aphanite.
Granular Diorite.
Porphyritic Diorite.

Aphanite is a rock, corresponding to Felsite among the Felstones, of so closely grained and even a texture that no crystals can be detected in it by the naked eye; a perfect passage can be traced from it into ordinary Granular Diorite, and there can be no doubt that it is the compact form of that rock.*

Granular Diorite is the form to which the term Diorite alone is usually applied. It is a mixture of crystals of Oligoclase and Hornblende, coarse enough to allow of its crystalline texture being readily recognised, and fairly uniform in grain throughout. Usually Granular Diorite contains a larger percentage of Hornblende than Felspar, and sometimes the former mineral so far predominates as to make up almost the whole of the rock.

Porphyritic Diorite† differs from the last variety in having, as its name implies, a porphyritic texture. Whereas in Granular Diorite no one part of the rock is more distinctly crystalline than the other, the present form consists of crystals set in a compact paste. The paste is probably Oligoclase, the crystals are of the same mineral with occasionally some of Hornblende, which is in some cases replaced by Mica. The paste is sometimes amygdaloidal. The Quartzless forms of this rock are more plentiful than the Quartzose.

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* The term Aphanite is not always used in the limited sense here assigned to it. It is often made to include all Basic rocks of so fine and close a texture, that their mineral composition cannot be learned by mere inspection. In this wider sense many Aphanites are the compact forms of Gabbro and other crystalline rocks—Basalt in fact.

† This is the rock called *Porphyrite* by Zirkel. The name is not desirable, on account of its resemblance to the objectionable noun Porphyry; and it has been used by different authors in different senses, till there seems little hope of ever tying it down to a definite meaning.

These three forms of Diorite correspond with the analogous varieties of Felstone thus:—

Aphanite.	Felsite.
Granular Diorite.	Granular Felstone.
Porphyritic Diorite.	Porphyritic Felstone.

Perfect passages exist from each form into the one next to it, and, as in the case of the Felstones, there is no doubt that they are merely varieties of the same rock, which have assumed different textures on account of a difference in the condition under which they were formed.

In some rocks, which in other respects correspond with Granular Diorite, Orthoclase is sparingly present. These form connecting links, when they are Quartzless, between Diorite and Syenite, and, when they contain Quartz, between Diorite and Hornblendic Granite.

C *b.—Melaphyres.*

Probably no name has been so ill used by petrographers as that of Melaphyr. It has been employed by so many different authors in different senses that by itself it has long ceased to bear any definite meaning. We may however usefully follow Zirkel in limiting it to rocks composed of Oligoclase and Augite with some Magnetite.

The grain of these rocks varies. They are occasionally porphyritic, very frequently compact, and glassy varieties are said to have been observed. They are also very often vesicular or amygdaloidal. As the name implies, the colour is usually dark.

C *c.—Basalts.*

The rocks grouped under this head are essentially mixtures of Labradorite and Augite, or some augitic mineral; they also contain Titaniferous Magnetite. In some varieties the Labradorite is replaced by Nepheline or Leucite. Olivine enters very generally into their composition, so frequently indeed that by some petrologists it is looked upon as an essential constituent. The Basaltic rocks may be grouped according to their texture under the heads of—

Tachylite, or Basaltic Glass.
Common Basalt, the compact form.
Anamesite, or finely crystalline Basalt.
Dolerite, or largely crystalline Basalt.
Gabbro, or coarsely crystalline Basalt.

The most coarsely crystalline members of the Basalt group are distinguished as *Gabbro*. In this rock the Augite is most commonly replaced wholly or in part by the allied mineral Diallage, and in this case the rock is often called *Diallage rock*. Gabbro is as a rule a very coarsely-grained rock, closely resembling Granite in texture, and it holds among the Basic rocks a place corresponding to that occupied by Granite in the Acidic class.

A Basalitic rock, whose grain is not so coarse as in Gabbro, but coarse enough to allow the constituent crystals to be readily recognised by the naked eye, is called *Dolerite*. Sometimes Hypersthene takes the place of Augite, and the rock is then known as *Hypersthene rock*. If the Labradorite is replaced by Leucite we get *Leucite rock*.

In many Dolerites Carbonate of Lime and Iron are present, intimately mixed up with the body of the rock. When in addition to these minerals Chlorite is also present, the rock is known as *Diabase*. There is every reason to believe that these Carbonates and the Chlorite were not present originally in the rock, but have been produced after its formation by the alteration of some of its mineral constituents. Hence Diabase is probably only an altered form of Dolerite.

If we suppose the grain of Dolerite to be so far reduced, that we can perceive in a general way that the rock is crystalline without being able clearly to distinguish its constituent minerals, we get the variety called *Anamesite*.

The rock generally known as *Basalt* is a still more finely grained form. This is a dark-coloured, apparently homogeneous rock, with a dull conchoidal fracture. So compact is it that it was for a long time looked upon as a simple mineral, but chemical analysis and microscopic examination prove it to have the same composition as Dolerite.

Even the close Anamesites and Basalts become occasionally porphyritic by the appearance in them of grains or crystals of Olivine, Labradorite, Augite, and Magnetite. The first mineral is said to occur more commonly in Basalt than in the other varieties of the Basaltic family.

		Silica.			
		Max.	Mean.	Min.	Max.
Acidic Rocks.	Granite	81·77	71·54	66·81	19·05
	Porphyritic Felstone..	81·05	74·27	67·54	14·97
	Felsite..............	81·36	76·69	71·52	12·24
	Pitchstone	73·70	72·65	70·10	12·34
	Quartzose Trachyte ..	82·47	76·58	72·26	16·19
	Obsidian	77·60	71·56	60·52	19·05
Intermediate Rocks.	Quartzless Trachyte..	67·09	63·74	60·01	21·03
	Minette	56·96	50·24	47·99	16·23
	Sienite..............	62·52	59·76	56·36	20·73
Basic Rocks.	Diorite	48·50	48·70	48·90	18·50
	Gabbro	53·76	50·15	43·50	20·77
	Dolerite	53·54	51·00	48·00	19·03
	Anamesite	53·08	50·47	46·80	14·87
	Basalt	45·9	43·47	36·68	28·67
	Tachylite	56·05	55·74	50·22	17·84

Both Dolerite, Anamesite, and Basalt put on slaggy, vesicular, and amygdaloidal forms.

The last term in the series is furnished by the glassy form known as *Tachylite*, which stands in the same relation to Basalt as Pitchstone does to Felsite. That Tachylite is only glassy Basalt is proved by numerous instances in which a passage can be traced from one into the other. Professor A. Geikie, in describing the Basaltic veins of the Island of Eigg, says, "towards the edge of the vein the grain of the rock is usually very close, passing sometimes through various stages of flinty Basalt into bright, black, lustrous Tachylite."*

C *d.—Corsite.*

The rocks in which Anorthite has been recognised as a constituent mineral are as yet but few. One of the best known is the so-called Orbicular Diorite of Corsica, but, as this is not a Diorite in the common acceptation of the term, it will be better to call it Corsite or Napoleonite.

The rock is a granular mixture of Anorthite, Hornblende, and a little Quartz.

The most noticeable variety occurs in Corsica; the rock there is made up of balls from one to three inches in diameter; each has a central kernel composed either of the Felspar or of Hornblende, and round this there wrap concentric coats first of one mineral and then of the other, so that a cross section shows rings alternately of a dark and light colour. Such a structure is called Concretionary, and is by no means uncommon in Crystalline rocks especially of the Basic class. Other rocks are known having the same composition as Corsite, but without concretionary structure.

For an account of another rock consisting of Anorthite and Hornblende or Augite see Chapter VII.

The above are all the Crystalline rocks we shall be concerned with for some time to come. The Foliated and Schistose rocks we shall defer till the chapter on Metamorphism.

We add a table showing the chemical composition of the principal varieties of the Crystalline rocks.

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* Quart. Journ. Geol. Soc. of London, xxvii. 299.

SECTION VI.—NON-CRYSTALLINE ROCKS.

We will now pass to the second great division in our lithological classification, namely the Non-crystalline Rocks.

Texture.—Under the head of texture we may notice that the binding cement in these rocks may be soft or small in quantity, in which case the rock is *crumbly* and *friable;* or it may be hard and plentiful, when the rock will be *firm* and *solid.*

According to the size of their particles these rocks may be subdivided into *Coarsely-grained*, *Finely-grained*, and *Closely-grained* or *Compact.*

In some coarsely-grained rocks lumps, sensibly larger than the majority of the particles, are scattered through the body of the rock. Such are called *Conglomerates* or *Pudding-stones*, when the larger portions are rounded; and *Breccias*, when they are angular.

Subdivisions of the Non-crystalline Rocks.—The composition of the Non-crystalline rocks is far less complex than that of the Crystalline rocks, and their classification hence becomes an easier matter. The great mass of them are made up of one or more of the four minerals, Quartz, Clay, Carbonate of Lime, or Carbon, and they fall naturally into four groups, according as their prevailing ingredient is the first, second, third, or fourth of these, and their classification will be as follows:—

1*st Class.—Arenaceous or Sandy Rocks.* Composed mainly of rounded or broken grains of Quartz. The cement may be either siliceous, argillaceous, calcareous, or a mixture of any of these three substances.

2*nd Class.—Argillaceous or Clayey Rocks.* Pure Clay, which is the main constituent of rocks of this Clay, is a hydrated bisilicate of Alumina. Besides Clay the majority of the Argillaceous rocks contain mixtures of Sand, Carbonate of Lime, and other minerals.

3*rd Class.—Calcareous Rocks or Limestones.* Composed of Carbonate of Lime, with admixtures of Sand, Clay, and other matters.

4*th Class.—Carbonaceous Rocks.* Composed of Carbon, Hydrogen, Oxygen, and Nitrogen, with earthy admixtures.

As in the case of the Crystalline rocks no hard lines can be drawn between these classes, since all sorts of intermediate forms occur. Thus for instance there are many rocks containing both Sand and Carbonate of Lime, which might be placed indifferently in the 1st class as Calcareous Sandstones, or in the 3rd as Sandy Limestones; but in a very large number of the Non-crystalline rocks, either Sand, Clay, or Carbonate of Lime is present in so much larger quantity than any other ingredient, that we are justified in establishing the subdivisions just given, and able without any difficulty to decide in which of them a given rock ought to be placed.

We may now notice some of the principal varieties of each class of the Non-crystalline rocks.

1.—ARENACEOUS OR SANDY ROCKS.

A mass of more or less rounded grains of Quartz, not bound together by any cement, constitutes *Sand*.

Rock Sand is a term applied to masses of Sand which hold together sufficiently to stand up in natural rocks, but are not firm enough to yield stone for building purposes.

When the Quartz grains are firmly bound together in any way, we get a strong rock and call it *Sandstone*. The term is generally restricted to those rocks in which there is not much difference in size among the grains. In most cases the solidity of the rock is due to a cement, which fills up the interstices between the grains and binds them together. If this cement be Carbonate of Lime, the rock is called a *Calcareous Sandstone;* if Quartzose, a *Siliceous Sandstone*. Very siliceous Sandstones with an even close grain are called *Cank*, *Cankstone*, or *Galliard*. Many Sandstones also contain Clay: such are called *Argillaceous Sandstones*. Sandstones containing recognisable bits of Felspar are called *Felspathic Sandstones*. Sandstones containing a large quantity of Peroxide of Iron are distinguished as *Ferruginous* or *Rusty;* they are red, brown, or yellow in colour (see p. 18).

If some of the particles of a sandy rock are larger than others, so that a freshly broken surface has a rough, gritty feel, the rock is called a *Grit* or *Gritstone*. The term however is not generally applied to *friable* sandy rocks, however coarse they may be, but is restricted to those which are *hard* and *firm*.

When a sandy rock contains pebbles of Quartz or Quartzose rock embedded in a finer ground-mass of Sand, it forms a *Siliceous* or *Quartzose Conglomerate.* The adjective is very generally dropped and the rock styled simply a Conglomerate, because the pebbles of a great majority of Conglomerates are Quartz; the reasons for this being, first, that Quartz is a substance very plentiful in the rocks of the earth's crust, and secondly, that on account of its great hardness it is able to survive in pebbles of considerable size wear and tear that grinds softer substances to powder. The rounded lumps in Conglomerates are of all sizes from small pebbles up to blocks some feet in diameter. In some cases the pebbles of a Quartzose Conglomerate are cemented together by substances other than Quartz, such as Carbonate of Lime or Oxide of Iron.

Some other Quartzose rocks will be noticed under the head of Metamorphic Rocks.

The grains of a rock that is decidedly sandy will scratch glass, and this test, which however it is seldom necessary to apply, may be used when there is any doubt about the composition of the rock. When the Quartzose element is disguised by the presence of a large mixture of a softer substance such as Clay, the rock may be pounded, and the powder drawn with pressure between the finger and a plate of glass; any Quartz grains that may be present will then make scratches.

2.—ARGILLACEOUS OR CLAYEY ROCKS.

Clay, the main ingredient of these rocks, is a mineral we have not yet had occasion to notice. It has been obtained in the first instance by the decomposition of a Potash or Soda Felspar, and perhaps can scarcely be properly described as a mineral, but should rather be called a product of decomposition. In ordinary parlance any substance that can be worked up with water, so as to become plastic or capable of being moulded, is styled Clay; and in this wide sense Clays, as might be expected, show considerable differences in composition. But if we separate from any clayey substance the mechanically mixed impurities, the residue will be a hydrated silicate of Alumina; and it is to the fact that Clay contains water in a state of chemical combination that its plasticity is due. Chemists are by no means agreed about the composition of pure Clays, and it is likely that there are several varieties differing from one another in the proportion of silica and the amount of water they contain. Many Clays however approximate very closely to a Hydrated Bisilicate of Alumina, with the formula—

$$2SiO_2,Al_2O_3+2H_2O.$$

or	Silica	46·6
	Alumina	39·5
	Water	13·9

The nearest approach to pure Clay is *Kaolin* or *China Clay*. The natural deposits contain grains of Sand, plates of Mica, and other impurities; and when these are washed out there remains a pure white plastic Clay, used for making porcelain and the finer kinds of pottery.

Pipe Clay is a similar white pure Clay, which shrinks too much from heat to be available for pottery purposes. It is important that both China Clay and Pipe Clay should be free from Iron, which acts as a flux and causes the Clay to melt instead of baking in the furnaces.

Pot Clays are less pure than China Clay, and the ware made from them is coloured and coarser: all that is required of them, is that they should form with water a plastic mass, and be capable of baking.

Still coarser Clays serve for *Brick Clays;* the finer varieties, consisting of a very finely divided and intimate mixture of Clay and Sand, are called *Brick Earth*. Brick Clays should not contain too much Iron, but a moderate quantity of the Protoxide is said to give strength and hardness to bricks.

Fire Clays are varieties which will stand intense heat without melting. They must be free from alkalies, alkaline earths, and iron, which act as fluxes. Fire Clays always contain a much larger percentage of Silica than is necessary to form a Bisilicate; part of this certainly in some cases exists as a mechanical mixture, partly as insoluble and partly as colloidal Silica. The Clay for instance whose analysis is given below contains Silica in both these states, while the residue is very nearly a Hydrated Bisilicate:—*

Silica as Sand	56·95
Silica soluble in hot solution of Carbonate of Soda	1·39

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* See Crookes and Röhrig, Metallurgy, iii. p. 559, and Percy, Metallurgy, i. 214, for further details of Fire Clay.

Residue after the above Silica is removed—

Silica	45·30
Alumina	34·08
Iron, Sesquioxide	3·27
Lime	0·87
Magnesia	1·14
Potash	3·05
Water	12·29

The following analyses will show the average composition of different kinds of Clay:—*

	(1)	(2)	(3)	(4)	(5)
Silica	49·44	46·38	66·68	46·32	65·10
Alumina	34·26	38·04	26·08	39·74	22·22
Iron Oxide	7·74	1·04	1·26	0·27	1·92
Lime	1·48	1·20	0·84	0·36	0·14
Magnesia	1·94	trace	trace	0·44	0·18
Water	5·14	13·57	5·14	12·67	9·86

(1) Common Pottery Clay, will not stand heat.
(2) Best Pottery Clay, burning white.
(3) Coarse sandy China Clay.
(4) Best Kaolin.
(5) Fire Clay, Stourbridge.

Loam is a mixture of Clay and Sand, the latter being present in sufficient quantity to allow of water percolating through the mass and to prevent its binding together. Clayey rocks which split into layers or beds are called *Shale; Bind, Blue-bind, Plate, Shiver* are other names applied by miners to the same rock. Shales containing a sufficient quantity of Iron Pyrites are used for the manufacture of Alum, and are called *Alum Shales.*[*] When there is a good deal of Sand present, the rock is called *Arenaceous* or *Sandy Shale*, or *Stone Bind*, or *Rock Bind*. These forms pass gradually into Argillaceous Sandstones and common Sandstone. Shales stained dark by vegetable matter are called *Carbonaceous Shale*, *Bass*, or *Batt*. When such Shales contain a sufficient quantity of bituminous matter to be used for the manufacture of Paraffin they are called *Oil Shales*. Such Shales pass gradually into Cannel Coal occasionally. The streak of Oil Shales is usually brown.

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* See also Catalogue of Specimens of the Clays and Plastic Strata of Great Britain in the Museum of Practical Geology, London. G. W. Maw.

Mudstone is a convenient name for clayey rocks that have the appearance of partially hardened masses of sandy mud.

Marl is Clay containing Carbonate of Lime; if the rock splits into plates, it is called *Marl Slate*.

Other clayey rocks will be noticed under the head of Metamorphic Rocks.

When Clay is present to any extent in rocks, they give out an earthy smell when breathed upon. Even the hardest clayey rocks can be worked down by pounding or grinding them with water into a more or less doughy and plastic mass.

3.—CALCAREOUS ROCKS OR LIMESTONES.

Most varieties of this class depend on the extent to which the Carbonate of Lime is mixed with clayey, sandy, and other impurities.

Chalk is a white Limestone, usually soft, containing sometimes as much as 94 to 98 per cent. of Carbonate of Lime. The more clayey varieties go by the name of *Chalk Marl*.

Some other Limestones are as pure as Chalk; thus some specimens of the Mountain Limestone contain only 4 per cent. of impurities. But in the majority of Limestones foreign matters are present to a large extent. When there is a considerable percentage of Clay, the rock is called an *Argillaceous Limestone*. The Lime obtained by burning some Argillaceous Limestone forms a mortar that sets under water: such are called *Hydraulic Limestones*.[†]

Limestones containing a large siliceous element are called *Siliceous Limestones*. When the calcareous part of such rocks has been dissolved out by the action of water, a sort of siliceous skeleton is left called *Rottenstone*. Passages sometimes occur from Calcareous Sandstones into Limestone, and the intermediate forms are called locally *Cornstones*. Some Cornstones contain so much more Carbonate of Lime than Sand that they are burnt for Lime in districts where purer Limestones are not easily obtained.

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[*] Roscoe, Elementary Lessons in Chemistry, p. 208.

[†] See Wagner's Chemical Technology, and Watts's Dictionary of Chemistry, Art. "Silicates of Calcium."

Limestones stained a dark colour by decomposed vegetable or animal matter are called *Carbonaceous* or *Bituminous Limestone;* such rocks often give off a fetid smell when struck by the hammer, and are then spoken of as *Fetid Limestone* or *Stinkstone*.

Limestones occasionally put on a conglomeratic or brecciated form, and contain pebbles or angular fragments of Quartz or other rocks.

A Limestone hard and close grained enough to take a polish is called *Marble*. Some of the so-called Marbles of commerce however are not Calcareous rocks at all.

Magnesian Limestones.—These rocks, which are mainly made up of Carbonate of Lime and Carbonate of Magnesia, are called Magnesian Limestones or Dolomites. Usually no distinction is drawn between these two terms; they are used, sometimes one and sometimes the other, as if they were only two different names for the same rock. Possibly, however, at least three distinguishable varieties of magnesio-calcareous rocks exist, and it may be convenient to restrict one of these terms to one form and the other to another.

Whether the carbonates exist in the rocks we are considering in a state of mechanical mixture, or of chemical combination, is not certainly known. Both Forchhammer* and Karsten found that certain Magnesian Limestones could be separated into two parts. One, which was soluble in cold acetic acid, had the following composition:—

Carbonate of Lime . .	97·13
Carbonate of Magnesia .	2·87

When this portion had been dissolved out, there remained an insoluble granular residue having the composition—

Carbonate of Lime . .	53·38
Carbonate of Magnesia .	41·42†

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* Bischof, Chemical Geology, ii. 49.

† Sterry Hunt has repeated these experiments, and finds that the conclusion arrived at is very approximatively, but not exactly, correct.—Silliman's Journ. 2nd ser. xxviii. 180.

The facts that the latter portion has nearly the theoretical composition of a double Carbonate of Lime and Magnesia, and that it is insoluble in cold acetic acid, led to the belief that it was a chemical compound. But insensibility to the action of acetic acid is a fact whose value has been somewhat diminished since the time when the experiments were made, for it has been lately shown, that the behaviour of this acid towards carbonates varies very considerably with the circumstances under which it comes in contact with them.*

We cannot say positively, therefore, whether the insoluble residue of the limestones operated on is a chemical compound or a mechanical mixture of the two carbonates. The insoluble portion has, however, the same composition as one of the forms of Bitter Spar, and, like it, is not acted on by cold acetic acid: it may, therefore, be looked upon as probably Bitter Spar; and, in speaking of it thus, we do not pronounce any opinion as to whether it is a chemical compound or not, for this is a point respecting Bitter Spar which is equally open to question. There is, then, probably, one form of magnesio-calcareous rock consisting of Bitter Spar and Carbonate of Lime. Other rocks of the same family contain, perhaps, no soluble portion, and consist essentially of Bitter Spar; and there may be others wholly soluble, consisting of Carbonate of Lime and Carbonate of Magnesia. If this be so, the following nomenclature may be usefully employed:—

Dolomite, a rock consisting essentially of Bitter Spar.

Dolomitic Limestone, a rock which is essentially a mixture of Bitter Spar and Carbonate of Lime, or of Bitter Spar and Carbonate of Magnesia.

Magnesian Limestone, a rock which is essentially a mixture of Carbonate of Lime and Carbonate of Magnesia.

In nature all these rocks contain frequently large quantities of sandy and clayey impurities, which give rise to sandy or marly varieties.

There are other calcareous rocks which have been produced by the alteration of some of the above forms. These will be described in the chapter on Metamorphism.

While we are dealing with compounds of Lime we may mention that Gypsum frequently occurs in sufficient quantity to form rock masses.

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* I am indebted to my friend, Dr. Thorpe, for calling my attention to this fact.

Limestone rocks may be readily recognised by touching them with a little dilute acid, when they will effervesce, the escape of gas being more plentiful as the rock is more pure. If the Limestone be powdered and dissolved in acid, acid being added in small quantities till effervescence ceases, any sandy and clayey impurities will remain behind, and by filtering and drying the residue its composition may be roughly determined. If clayey, it will work up into a plastic mass with water, and give out an earthy odour when breathed upon; if sandy, its particles will scratch glass. In practice however it is seldom necessary to take all this trouble; Limestones are soft enough to be scratched even with the blunt edge of a hammer, and have a look which is soon recognised after a little experience. They are also dissolved away by rain-water, and their exposed surface has a cavernous and worn shape, not easily described in words, though to get to know the look of it is easy. By such signs the practical geologist soon learns to recognise a Limestone; he may distinguish the earthy varieties by their smell when breathed upon, and in any sandy forms grains of Quartz can generally be detected with a pocket lens on a freshly broken surface, or will be seen sticking up on a weathered face.

Magnesian Limestones, which approach Dolomite in composition, effervesce feebly, or not at all, with cold acids; readily, when powdered, in warm acid. When Carbonate of Magnesia is present in quantities smaller than in Dolomite, it is sometimes necessary to use chemical analysis to be sure of its presence; very often however even in such cases the rock contains cavities, the walls of which are coated with crystals of Bitter Spar, and these may be distinguished from Calcite by their feeble effervescence with acids, and by their faces being frequently curved and somewhat pearly in lustre. By these tests we can sometimes form a fair guess that a Limestone is Magnesian; frequently, however, nothing short of analysis will settle the point.

Gypsum will not effervesce with acids, and is soft enough to be scratched with the finger-nail. These tests and a little acquaintance with specimens will enable the student to recognise it.

4.—Carbonaceous Rocks.

There are only two varieties sufficiently common to deserve notice here, *Coal* and *Graphite*.

Coal is too well known to need any description. In composition it differs from woody fibre only in containing a larger percentage of Carbon and a smaller percentage of Oxygen and Hydrogen.

The following table gives the average composition of woody fibre and peat and of the different kinds of Coal, and shows how by the gradual removal of the Oxygen and Hydrogen we pass, step by step, from the first to a substance in which scarcely anything but Carbon is left.

	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Ash, &c.
Wood	47·89	5·07	43·11	0·73	3·20
Peat	54.1	5·6	40·1		4·6 to 10·0
Coal from Borneo	54·31	5·03	24·22	0·98	15·46
Lignite	69·3	6·6	25·3		0·8 to 47·2
Cannel Coal	66·4	7·54	10·28	1·36	13·82
Splint Coal	75·58	5·50	8·33	1·13	5·46
Barnsley Steam Coal ..	80·68	4·9	8·44	1·55	3·69
Hutton Seam House Coal	84·28	5·52	6·22	2·07	1.89
Anthracite	91·44	3·46	2·58	0·21	2·31

The gradual transition from Wood, which is about half Carbon, to Anthracite, which is nearly all Carbon, is shown still more clearly in the following table, taken from Dr. Percy's "Metallurgy," in which the total amount of Carbon in each variety is reckoned as 100, and the Nitrogen and Ash are neglected.

	Carbon.	Hydrogen.	Oxygen.
Wood	100	12·18	83·07
Peat	100	9·85	55·67
Lignite	100	8·37	42·42
Tenyard Coal of South Staffordshire .	100	6·12	21·23
Tyne Steam Coal	100	5·91	18·32
Pentrefelin Coal	100	4·75	5·28
Anthracite	100	2·84	1·74

Besides this resemblance in chemical composition to woody fibre, microscopic examination frequently shows in Coal portions still retaining the characteristic texture of plants and other traces of vegetable remains.

On such general grounds the vegetable origin of Coal has been for a long time universally admitted, and this view has been of late years materially strengthened and rendered more definite by the discovery of the fact that some Coals are made up almost entirely of the spores and spore-cases of plants closely allied to the modern Club-mosses. In the cryptogamic or flowerless plants multiplication is effected by bodies called *Spores*, which correspond, as far as their ultimate products are concerned, to the seeds of flowering plants. In some cases it is known that there are two kinds of spores, *microspores* or little spores, and *macrospores* or large spores, the first producing the fertilising matter, and the second developing ovules or germs. In the common Club-moss one kind of spores only has been observed, and its mode of reproduction is not understood. The spores are contained in bags called *Sporangia* or *Spore-cases*. In some Club-mosses and Horse-tails the sporangia are placed within cones or spikes, consisting of scales or leaves overlapping each other, and the sporangia are lodged in the spaces between the scales. Now among the commonest of the fossils found in the strata among which Coal occurs is one that goes by the name of *Lepidostrobus*. In external appearance it resembles strongly the spikes of the modern Club-moss. Dr. Hooker* obtained specimens of these cones with the internal structure preserved, and showed that they consisted of scales supporting sporangia, which contained spores marked with a triradiate ridge on their under side. In the arrangement of the scales, the attachment of the sporangia, and the shape and markings of the spores, these cones correspond with those of the Club-moss. Dr. Robert Brown† afterwards described a fossil cone called by him *Triplosporites*, which agrees with a modern lycopodiaceous plant, *Selaginella*, in containing both large and small spores, the microspores being found in both genera on the middle and upper scales of the cone, and the macrospores on those of the lower portion. Mr. Carruthers‡ has since examined another fossil cone, which he has named *Flemingites*, the sporangia of which show a triradiate marking on their underside, and agree with those of Lepidostrobus in containing only microspores.

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* Memoirs of the Geological Survey of England and Wales, vol. ii, part 2, p. 440 (1848).

† Transactions Linnean Society, xx. 469 (1851).

‡ Geol. Mag. ii. 431; vi. 151, 289.

Now, as far back as 1840, Professor Morris figured some small bodies found in the coal of Coalbrook Dale, of the nature of which he was at that time unaware.* These bodies agree so exactly in shape, size, and the triradiate marking with the spores or spore-cases detected by Hooker, Brown, and Carruthers in the cones just described, that there can be no doubt that they have been shed from one or other of them, and the coal in question is certainly made up in part at least of the spores of a lycopodiaceous plant. Similar bodies have been observed by Professors Balfour and Huxley, Mr. Binney, and others, in other beds of Coal, and in some cases, the Better Bed of Bradford for instance, the seam is almost entirely made up of them. The plant to which *Lepidostrobus* belonged is extremely common in the beds associated with Coal; it is called *Lepidodendron*, and specimens of it with the cones attached to the branches are by no means uncommon. We can now, then, go further than the general statement that Coal is of vegetable origin; we know that among the plants which contributed to its formation one of the commonest was a close ally of our present Club-moss, and that, in some cases at least, it was the spores of that plant that furnished nearly all the material of the fossil fuel. It is worthy of note that the spores of the Club-moss are so highly inflammable that they are eminently suited to give rise to a combustible substance like Coal.

There is one other little point to which we may call attention, because it shows that a mass of the spores of Lycopodium is in other respects well fitted to give rise to a substance like Coal. Dr. J. Stenhouse remarks,† that, while the amount of Nitrogen in Coal, and consequently the quantity of Ammonia which it yields when subjected to destructive distillation, is very large, the stems and trunks of trees, when they undergo the same process, yield scarcely any amount of nitrogenous matters. These parts of plants therefore do not seem the right material to give rise to Coal. Both Lycopodium-spores, however, and Peat yielded large quantities of Ammonia when destructively distilled, and they are therefore a much more likely source to look to. Peat, however, and apparently Lycopodium-spores, did not yield Aniline, Quiniline, Picoline, and other bases so abundantly furnished by Coal, but a distinct group of bases in their place; hence it is probable that the plants which furnished the material of Coal, though they were closely allied, were not identical with the modern Club-moss and the plants out of which our Peat is formed, for it is a well-known fact that the bases yielded by the destructive distillation of plants are different in different plants.

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* In Prof. Prestwick's Paper on the Geology of Coalbrook Dale, Transactions Geol. Soc., 2nd series, vol. v. plate xxxviii. figs. 8—11.

† Phil. Transactions, 1850, pp. 54, 55, 59.

The amount of spores necessary to form a seam of Coal is so enormous, that some little hesitation may be felt at first in accepting the view that some Coals are made up of little else but these minute bodies. Large accumulations, however, of vegetable matter of a similar character have been observed in recent times. Dr. John Davy describes a shower of a "sulphurous substance" in Inverness-shire in 1858.* The "sulphurous substance" was found to be the pollen of the Fir (*Pinus sylvestris*); it lay in some places to a depth of half an inch, and was noticed at points thirty-three miles apart. Sir John Richardson informed Dr. Davy that the surface of the great lakes in Canada is not unfrequently covered with a scum of the same pollen. Similar occurrences have been observed in the forests of Norway and Lithuania.

In connection with this subject the reader may further consult the papers mentioned in the foot-note below.†

We will in a subsequent chapter explain how the materials of Coal were collected together and brought into their present shape.

The chief varieties of Coal are as follows:—

Lignite or *Brown Coal* sometimes consists of a matted mass of stems and branches of plants, still retaining their woody fibre and only partially mineralised. They have a low heating power, usually make a good deal of ash, and sometimes give off an offensive odour when burning.

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* Proceedings Royal Society Edinburgh, vol. iv. p. 157 (1859). I am indebted to my friend Mr. L. C. Miall for calling my attention to this and the paper last quoted, and for other valuable assistance in connection with the subject in hand.

† Dawson, Quart. Journ. Geol. Soc., ii. 132, x. 1, xv. 477, 626, xxii. 95; Annals of Nat. History, 1871, p. 321; Silliman's Journal, Ap., 1871; Acadian Geology, 2nd ed., pp. 138, 461, 493. Quekett, Quart. Journ. Microscopical Soc., No. 6, p. 43; Transactions Microscopical Soc., ii. 34. Bennett, Transactions Royal Soc. of Edinburgh, xxi. pt. i. p. 173. Balfour, ditto, p. 187. Huxley, Critiques and Addresses, p. 92. Williamson, Macmillan's Magazine, xxix. 404. Binney, Manchester Lit. and Phil. Soc., March 1874. Bischoff, Chem. Geology, i. 258.

The best *Cannel Coal* is compact and has a shining lustre, with a conchoidal fracture, and does not soil the fingers. It is of great value for gas-making, and owing to the large proportion of gas which it yields it will burn with a clear flame like a candle, whence its name. There are however all sorts of inferior varieties, and from the most impure of these a gradual passage often takes place into very carbonaceous black Shale. These imperfect Cannels are called in some parts of England Stone Coal, a term applied in other parts to Anthracite.

The ordinary Coals used for household purposes vary much in character. Some varieties, known as *Caking Coal*, fuse into a pasty mass as they burn, and require frequent poking to keep them alight. Others burn without caking. The amount of ash too is very variable; some Coals choke up the fireplace, others, like the Kilburn Coal of Derbyshire, may be burnt the day through and not leave a teaspoonful of ash. A very beautiful variety, known as *Cherry Coal* in Scotland and *Branch Coal* in Yorkshire, has a shiny resinous lustre, lights readily, burns cheerfully, and leaves little ash.

The above-named and other similar varieties of Coal are usually classed together as "Bituminous:" the term is not chemically correct, for though the Coals contain the constituents of Bitumen, they do not contain Bitumen itself. On the other hand, Anthracite, which is nearly pure Carbon, is described as Non-bituminous. The Coals called *Splint*, *Hard*, or *Steam Coal* are intermediate in composition and properties between "Bituminous" Coals and Anthracite. They are more difficult to light, but have a greater heating power than "Bituminous" Coal. They are of great value for locomotives and marine engines. Some, like the Barnsley Steam Coal, consist of thin semi-anthracitic layers alternating with others of a more "Bituminous" character.

Anthracite is heavier, harder, and has a more thoroughly mineralised look than "Bituminous" Coal, qualities well expressed by its popular name, *Stone Coal*. It rarely soils the fingers, has very frequently a sharp conchoidal fracture, and a brilliant lustre. Other varieties are dull, or break into small cubical lumps. It is difficult to light, but, when ignited, gives out intense heat, and burns without flame and with little smoke.*

Graphite, Plumbago, or *Black Lead* occurs as an accessory constituent of Granite, Gneiss, and other rocks, in veins or pockets, and occasionally in a state of approximate purity in beds. It consists of Carbon with about five per cent. of impurities, such as Silica, Alumina, and Oxide of Iron. There is good reason in many cases to believe that it is only an extreme form of Anthracite, that is, it is a Coal from which the gaseous elements have been completely withdrawn.

The student who wishes to learn how to recognise rocks and minerals will find it necessary to study and handle actual specimens. With practice he will gradually become able, by means of the descriptions and tests given in the preceding pages, to name correctly a large number of the commoner species, specially in those cases where the grain of the rock is large enough to enable the constituent minerals to be picked out separately. But in some instances, such as very compact Crystalline rocks, the composition can be ascertained only by examining thin transparent slices under the microscope. This is a branch of Lithology beyond the scope of an elementary treatise; those who wish to pursue it may refer to "The Microscope in Geology," *Geological Magazine*, iv. 511. Presidential Address, "Transactions of the Geological Society of Ireland," ii. 98. Sorby, "On the Microscopical Structure of Crystals," *Quart. Jour. Geol. Soc.*, xiv. 453. Zirkel, "Die mikroskopische Beschaffenheit der Mineralien und Gesteine." Rosenbusch, "Mikroskopische Physiographie der petrographisch wichtigen Mineralien."

SECTION VII.—PETROLOGY.

We have now learned the main facts that can be ascertained about the principal rocks of the earth's crust by an indoor examination of hand specimens. We have next to inquire what additional information we shall gain when we study rocks on a large scale in the field.

Outdoor work will reveal to us many peculiarities of structure too large to be shown by hand specimens. But instead of giving a bare list of these here, it will be more convenient to defer the description of most of them till we come to inquire about the agents and the methods by which they were produced. Two points however it will be desirable to notice at once.

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* For fuller details of the different varieties of Coal, see Crookes and Röhrig, Metallurgy, iii. 413—470; Percy, Metallurgy, i., chap. on Fuel.

Stratification or Bedding.—A very large number of rocks, when they are exposed on the face of a quarry, on a river bank, or on a sea cliff, are seen to be cut up by a number of parallel planes of division into layers, which separate more or less readily from one another, so that the rock consists of a number of flat tabular masses, each keeping pretty much the same thickness, laid one on the top of the other.

Such a structure is called *Stratification* or *Bedding* from the Latin word *stratum* a bed, the rock is said to be *stratified*, and the layers are called *Beds* or *Strata*.

Fig. 6, which is a sketch of an actual quarry, is an instance of a group of stratified beds.

Beginning at the top the beds are as follows:—

	Lithological Character of Bed	Thickness.	
		Ft.	In.
1.	Reddish sand	1	6
2.	White marly limestone, upper part fissile or splitting into thin layers, lower part lumpy or rubbly	3	6
3.	Brown clay splitting into thin layers	1	9
4.	Soft sand	1	0
5.	Hard, white, marly limestone	2	0
6.	Brown clay splitting into thin layers	1	6
7.	White marly limestone	2	0
8.	Soft brown sand	1	9
9.	Hard cream-coloured limestone		9
10.	Soft brown sand	8	0
11.	Solid grey blocky limestone	6	0
12.	Sandy clay	5	0
13.	Stiff blue clay	4	0

Relation between Stratification and Crystalline or Non-crystalline Texture.—In a very large majority of cases we shall find, that, *if a rock is stratified, it is also Non-crystalline.*

And we shall also find that *a very large number of the Crystalline rocks have no bedded structure, or are unstratified.*

There will be exceptions to these generalisations. We shall meet with rocks which are bedded and crystalline as well; but when we come to inquire how these rocks were formed, we shall find that, in most cases, either they were originally non-crystalline, and have been subsequently altered so as to acquire a crystalline texture, or that their

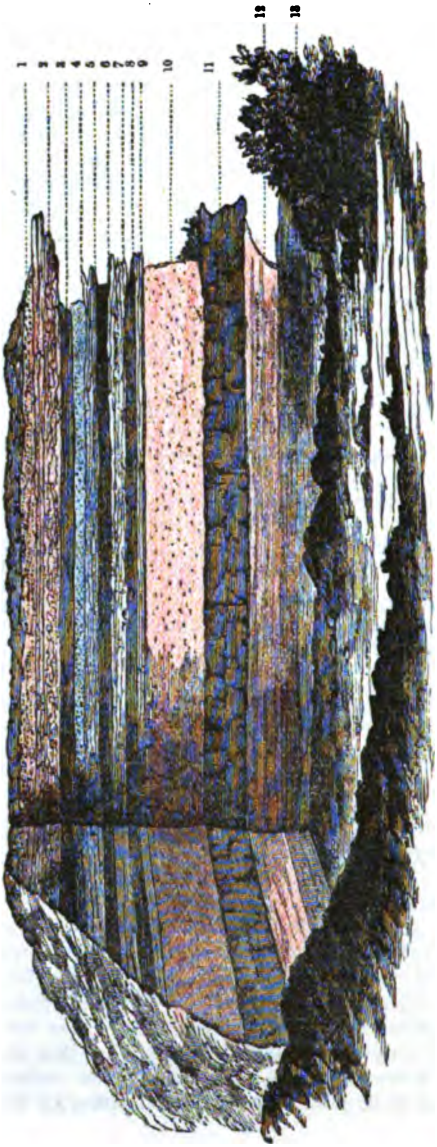

Fig. 6.—Quarry in Stratified Rocks.

bedding was obtained in a different way from that of the non-crystalline stratified rocks. These and a few other exceptions will be better understood when the reader has gone through the chapters on the formation of rocks.

Fossiliferous and Unfossiliferous Rocks.—Again, in many rocks we shall find what are undoubtedly the remains of animals and vegetables, shells of molluscs, corals, bones and teeth of fish, reptiles, and other creatures, leaves, stems, and fruits of trees and plants. Sometimes these are scarcely altered at all from their original condition; sometimes the substances of which they originally consisted have been replaced by various minerals, the change having occasionally been produced so gradually that not only the external form but all the minute details of internal structure are preserved; sometimes only an impression or cast remains.

All such remains are called *Fossils*, rocks containing them are spoken of as *Fossiliferous;* rocks, from which they are absent, as *Unfossiliferous.*

In nearly every case we shall find that *a Fossiliferous Rock is also Non-crystalline and Stratified.*

In some rare instances we may meet with fossils in Crystalline unstratified rocks, but these will be so very few, that *we shall come to look upon rocks of this class as Unfossiliferous.*

Petrological Classification of Rocks.—Subject then to certain exceptions, not relatively very numerous, and some of them more apparent than real, Petrological investigations lead us to arrange the rocks of the earth's crust into two classes having the following distinguishing characters:—

1st Class.	2nd Class.
Crystalline.	Non-crystalline.
Unstratified.	Stratified.
Unfossiliferous.	Fossiliferous.

Terms connected with Stratification.—We may conveniently define here a few terms used in connection with Stratification. The thicker layers of bedded rocks are usually spoken of as *Beds* or *Strata*, and the thinner as *Laminæ* or *Stratula*. Sometimes each of those portions of a group of bedded rocks, which has the same mineral composition throughout, is called a Stratum; and, if this stratum can be split up into a number of subordinate layers, each is called a Lamina. Thus in Fig. 6, we should say we had a stratum or bed (No. 3) of brown

Clay overlying a stratum or bed (No. 4) of soft Sand, the first consisting wholly of Clay, the second wholly of Sand. The brown Clay however can be split up into a large number of thin parallel layers, each of these is called a *lamina*, and the rock is said to be *laminated* or *fissile*. The distinction between strata and laminæ is somewhat vague, but the circumstances do not admit of exact definitions or hard lines. Single beds of rock sometimes are as much as two hundred feet in thickness, but such are rare; about five feet would be a general average. Lamination may go to almost any extent; in some very finely laminated rocks as many as thirty or forty layers may be counted in the thickness of an inch: such beds are usually clayey in composition, and are sometimes called *Paper Shales;* very finely laminated siliceous and calcareous rocks are however also met with.

When, as in Fig. 6, the upper and under bounding surfaces of the beds are parallel, so that each bed keeps the same thickness, the bedding is said to be *Regular*. A rock which is regularly and not very thickly bedded, so that it can be split up into slabs for paving, is called *Flaggy*, or a *Flagstone;* if the layers are thin enough for roofing purposes, a *Tilestone*.* The majority of Flagstones and Tilestones are Sandstones, but some Limestones, and even some hard Argillaceous rocks, yield Flags and Tiles. When beds thin away, the bedding is *Irregular* or *Wedge-shaped*, as in Fig. . A bed which thins away in all directions is called *Lenticular* or *Lens-shaped*.

This is all we will give here under the head of Petrology. There are many points yet to be noticed respecting the structure of rocks on a large scale; but we shall find it the best plan to take these one by one, as opportunities occur, while we pursue our inquiries into the way in which rocks were formed. Whenever, from time to time, we find that we have gathered knowledge enough to enable us to understand how any great structural peculiarity was produced, we will describe that structure and the way in which it arose.

Descriptive Geology. Summary.—Let us now take stock of the knowledge we have gained from Descriptive Geology.

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* This term, and not Slate, ought to be used for those rocks which split into roofing slabs along planes of bedding. We shall see by-and-by that the planes which bound roofing slates are not planes of bedding.

To the substances which make up the earth's crust we gave the general name of Rocks.

Rocks we found to be mechanical mixtures of certain definite chemical compounds called Minerals.

The number of mineral species which enter to any appreciable extent into the composition of rocks we found to be small, and the chemical elements of which these rock-forming minerals are composed to be not more than twelve in number.

By an indoor examination of hand specimens, or Lithology, we were led to a threefold classification of rocks.

1*st*. *Crystalline Rocks*, in which crystals appear with sharp angles and unrounded edges, but not arranged in any regular order.

2*nd*.—*Schistose Rocks*, which differ from the last in having their mineral components arranged more or less in separate layers, a structure which is expressed by the word Foliation.

3*rd*.—*Non-crystalline Rocks*, in which the mineral components appear in the shape of grains more or less rounded, or chipped and broken.

An examination of large rock masses in the field, or Petrology, leads us to a twofold classification of rocks.

1. *Stratified Rocks*, which are arranged in parallel layers, beds, or strata.
2. *Unstratified Rocks*, which possess no such bedded structure, or possess it in a minor degree.

We further found that the great mass of the Crystalline rocks are Unstratified, and the great mass of the Non-crystalline rocks are Stratified. In the latter too we frequently meet with Fossils; from the former Fossils are almost invariably absent.

So that a mere examination of the composition, structure, and contents of rocks led us to arrange them in the two following classes:—

1st Class.	2nd Class.
Crystalline.	Non-crystalline.
Unstratified.	Stratified.
Unfossiliferous.	Fossiliferous.

Lastly, we pointed out that this classification was liable to exception, and was otherwise imperfect, but that it was the best we could arrive at in the present state of our knowledge. This leads us on to inquire whether a further study of rocks will not tell us something more than we yet know about them, which will enable us to arrange them in a more satisfactory manner. In the next three chapters we shall find that what we want for the purpose is a knowledge of the way in which rocks were formed, and that, when we have mastered this branch of Geology, a natural and consistent classification follows from it as a matter of course.

CHAPTER III.

DENUDATION.

Process of time worketh such wonders,
That water, which is of kind so soft,
Doth pierce the marble stone asunder
By little drops falling from aloft.
WYATT.

SECTION I.—PRINCIPLES ON WHICH THE INQUIRY INTO THE ORIGIN OF ROCKS IS BASED.—EXAMPLES OF THE APPLICATION OF THESE PRINCIPLES.—DEFINITION OF DENUDATION AND ENUMERATION OF DENUDING AGENTS.

WE have now made the acquaintance of the chief materials out of which rocks are made up, and have learned what are the great classes into which we subdivide the rocks themselves, according as we look at them from a Lithological or Petrological standpoint.

It would be possible still to limit our attention for some while to purely Descriptive Geology: we might take one by one each individual species of the great classes of rocks, and describe its lithological composition, and the structural characteristics which it shows when studied on a large scale; and this we might do without saying a word about the causes that produced the rock and impressed on it its peculiar structure. Then we might in separate chapters treat of the origin of rocks and of rock structures.

But, beyond a claim to systematic arrangement, such a scheme would possess no advantage whatever, and it would be attended by a serious evil. It would lay upon the mind of the student a burden too heavy to be borne, in that it would compel him either to carry in his memory a huge mass of bare facts up to the time when he reached that part of the book where the explanation of these facts is given; or, if, as is most likely, he found this beyond his powers, it would oblige him to be continually turning back, when the meaning of any fact was explained under the head of Historical Geology, to the description of that fact under Descriptive Geology.

We will therefore no longer linger in the purely descriptive part of our subject: we will go on to describe the different kinds of rocks in detail, but we will put side by side with the description of each an explanation of the way in which it has been formed. Thus the subject will be rendered less dry, and a great strain on the memory will be avoided.

But the question may be very reasonably asked at the outset, How do we know that there has ever been such a thing as formation of rock? Are we sure that the rocks have not been all along such as we see them now, and that the earth's crust did not come into being in the identical state in which it is at the present day?

There are a host of facts that enable us to give a decided No in answer to such suggestions. One of these, the occurrence of fossils in the heart of masses of rock, which has been noticed in the first chapter, is alone sufficient to settle the question. And very slight observation of what is going on every day before our eyes is enough to convince us that, for as far back as the earth has been anything like what it is at present, the rocks of its surface must have been constantly undergoing wear and tear, and that fresh rocks must have been forming without cessation out of their ruins. The whole of this and the next chapter will be taken up with a statement of the facts on which this assertion rests, and when the reader has reviewed the evidence, he will see that but one conclusion, the one just stated, can be drawn from it.

Principles on which the Origin of Rocks are determined.—The grand principles that must guide us in our speculations as to the origin of rocks are few and simple; but a very extensive range of knowledge is necessary to enable us thoroughly to apply them. We have first to inquire whether there are any substances now in course of formation which are identical with rocks of the earth's crust, or any which, if not actually identical, could be made so by modifications which it is reasonable to suppose they would be likely to undergo. If we do find, as we do, any such substances, we then study the causes which are now producing them, and conclude that the rocks which they resemble were produced in bygone times by similar causes.

In this way we are able to give a satisfactory account of the formation of many rocks. There are others which cannot have been produced by any causes that come within the reach of our actual observation; but even in the case of these we can form reasonable conjectures how they arose and what changes they have gone through.

We will begin with an inquiry into the origin of some of the Non-crystalline bedded rocks. These we shall find have been formed by the breaking up of some pre-existing rock, and in nearly all cases, when we trace back their history far enough, we learn that they sprang first of all from some one of the Crystalline rocks.

It would seem at first sight more natural to take the forefathers first and the descendants afterwards; the present arrangement has been chosen, as better suited to an elementary treatise, for the following reasons. The bedded rocks are more familiar to the generality of people than the great mass of the crystalline. Further among the causes that took part in the formation of bedded rocks are some of the commonest operations of Nature, so common indeed that their importance was long overlooked through sheer familiarity. These processes are going on every day under our eyes and can be studied by every one. There is this advantage then in directing the attention of the student first of all to the formation of this class of rocks; he can, whoever and wherever he be, observe for himself some of the steps by which they have been produced, and test by his own observation the correctness of the teaching which is put before him. The processes, on the other hand, to which a great part of the Crystalline rocks are due, operate unseen to a large extent at considerable depths below the surface; and when they do break forth and come within the range of observation, their sphere of action is confined to certain limited tracts of the earth's surface, which many persons have no chance of visiting.

Example of the Determination of the Origin of a Rock.—To make a beginning here is an instance of the way in which we ferret out the steps by which a particular rock has been formed.

Here is a bit of coarse Gritstone, and side by side with it let us lay a piece of coarsely grained Granite. The two are singularly alike, and in both we can readily distinguish the three minerals Felspar, Quartz, and Mica. The specimens might well be supposed by a casual observer to have been broken off the same crag, and if the two tors from which they were taken are viewed from a little distance, they are so similar in outline and look, that any one might be pardoned for supposing they were made of the same rock. But if the blocks be scanned a little more closely, specially if they be examined with a pocket lens, an important difference will be detected between them. In the Granite there are crystals with their angles pointed and their edges sharp; in the Gritstone, though the crystals may not be much altered, yet a certain amount of rounding off has taken place in both angles and edges. There can be no question that the Gritstone has been formed by the breaking up of a rock identical with the Granite specimen before us, and that in the process the crystals have lost something of their sharpness of outline. Our next question will be, What has done this? Let us visit the rocky tor from which our specimen of Granite was taken, and we shall not have to wait long for an answer.* The outer surface of the rock is evidently crumbling away, parts readily fall off in a coarse powder, the grains of which are crystals rounded in just the same way as in the Gritstone before us: large quantities of a similar powder are spread round the base of the tor, and fill cracks or hollows on its surface. The Gritstone holds together a little more firmly than this powder, but otherwise there is no difference between the two, and the conclusion is irresistible that the former is nothing else than a quantity of the latter, that has been in some way or other bound together into a moderately firm rock. If now we turn over in our minds what is constantly happening to this Granite tor, we shall readily understand how it is that it is crumbling away. Rain beats upon it, and has power to decompose and dissolve part of the cement by which it is held together; the water also, as it streams off the rock, washes over it the coarse grains lying on its surface and these grind it away like emery or a file; the wind drives against it the same wearing implements with the same effect; frost expands water contained in chinks or crevices, and forces off fragments: these and similar agents are incessantly at work, and by these the crag is being broken up and the heap of debris, which surrounds and partly buries it, has been formed and is constantly being added to.

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* It will be noted here that though mere lithological examination will in this case help us a little towards learning the way in which the Gritstone has been formed, it is only by out-door study that we can realise all the steps in the process.

By methods like those just described the materials, out of which our Gritstone is built up, were obtained: but the history of its formation is not yet complete. If we visit the quarry from which our specimen was taken, we shall find the rock arranged in layers, beds, or strata, each layer being marked off by a clear plane of division from that above and below it, and likely enough we may find, between some of the beds, layers of Clay, Limestone, or other rocks. No such bedded arrangement exists in the debris that surrounds the Granite tor; and therefore, though the materials for making a Gritstone are certainly to be found there, they must undergo some further process of arrangement, before they could give rise to a rock like that of which our specimen formed a part.

Not far from the foot of the Granite tor there runs a rivulet, and in fine weather it is clear enough to allow us to count the stones on the bottom. But after heavy rains the water pours down thick and turbid: fill a glass from the brook and let it stand: the water soon becomes clear, and a quantity of sand and mud, which was the cause of the turbidity, settles to the bottom: take out some of the settlings, and spread it in the sun to dry, it is nothing else but some of the finer part of the rubbish around the tor produced by the weathering of the Granite. It has been washed down the sloping bank by rain, and is being swept forward by the current. Now return to the rivulet; by a little attentive listening we can detect amid the rushing of the torrent a harsh, grating sound rising from beneath the water; this is caused by the coarser parts of the rubbish, which have been swept down into the stream, but which, being too heavy to be carried suspended in the water, are being pushed and rolled along the pebbly bottom. Thus the ruins of the Granite, coarse and fine alike, are being always carried forward; and when the rivulet falls into a larger brook and this again into a river, the waste matters travel on along with the contributions of the other feeders. The journey goes on till the river enters the still waters of a lake or of the sea: the stream then loses its velocity and therefore its power to carry any further; and the matters, which it has brought so far, all sink, sooner or later, to the bottom, and are spread out in layers approximately horizontal. In the intervals between two floods each layer will have time to harden a little before the next layer is placed upon it, and so a plane of separation between the two will be produced, and the deposit will have a bedded or stratified structure given to it. Further the velocity, which is sufficient to sweep along fine mud, is not able to move coarse sand, and hence at one time the former alone, and at others the two together, will be laid down beneath the still water. In this way the deposit will come to have in it layers of different degrees of coarseness and different composition. Again the heavy materials can at no time be carried so far out into the lake as the lighter and finer; and thus the stuff brought down will be, so to speak, sorted, coarse deposits will prevail near the mouth of the river, and will thin away in a wedge-shaped form, and be replaced by finer beds, as we advance towards deeper water. All this is found to be the case, when we drain lakes and cut into the accumulations which have been formed beneath their waters.

The stratified structure of the Gritstone mass, of which our specimen formed a part, is so exactly similar to that of deposits forming nowadays beneath still water in the manner just described, that we have no hesitation in ascribing it to the same cause which is giving them their bedded arrangement, and every step in the history of its formation is now clear to us. Its materials were furnished by the atmospheric wear and tear of Granite: they were washed by rain down hill-slopes into running streams, carried forward during floods into bodies of still water, and there they came to rest in layers laid one over the other by successive freshets: the bands of clay lying between the different beds of Gritstone, were formed in the same way, when the streams were lower and had not power to carry anything heavier than fine mud.

Rocks like this Gritstone, because they are made up of broken pieces of pre-existing rocks, are sometimes spoken of as Clastic (κλαστός, broken) or Derivative: and because they have been formed under water they go by the name of Subaqueous. Those derivative rocks, which have been formed not by the mechanical wear and tear of pre-existing rocks, but by the chemical decomposition of their constituents, are sometimes called Dialytic, but the distinction is not of much importance.

Repeated observations, similar to that just described, bring home to us the conviction that the solid matters, which form the surface of the earth, are constantly undergoing wear and tear; that the loose rubbish thus produced is being incessantly conveyed by the agency of rain and running water from higher to lower levels, till at last it comes to rest beneath large bodies of still water, where it is spread out in layers approximately horizontal; and that it is in this way that a large part of the bedded rocks of the earth's crust have arisen.

Denudation.—The process by which the surface of the ground is broken up and its ruins carried away, is known as Denudation, and the agencies by which this is effected, as Denuding Agents. A thorough grasp of the way in which Denudation works, lies at the root of all sound geological knowledge, and we will devote the rest of the present chapter to this subject.

Enumeration of Denuding Agents.—Denuding agencies may be classed under the following heads.

1. Rain. 2. Running Water, whether above or below ground. 3. Frost and Frozen Water. 4. Wind. 5. Animal and Vegetable agencies. 6. The Sea.

The first five are generally classed together as Subaerial, Atmospheric, or Meteoric Denuding agents. The denudation wrought by the sea is distinguished as Marine.

SECTION II.—HOW DENUDING AGENTS WORK.

We will now look at the way in which each of the denuding agents just enumerated works, and the results it produces.

We shall have to consider each first as a *producer*, secondly as a *carrier* of waste.

1.—RAIN.

Rain acts on the surface of the ground in two ways, Mechanically and Chemically.

Of the water which falls upon the earth from the clouds part rises again into the air by evaporation, or is taken up by plants; part streams over the surface, and is at last collected into brooks; part sinks into the ground, and, after pursuing for a longer or shorter distance an underground course, rises again in springs. We have here to deal with that part which flows over the surface, before it becomes gathered into a definite channel.

Mechanical Action of Rain.—Water during this portion of its course exerts an important mechanical effect as a carrying agent: any loose surface matter produced by the decomposition of the rock beneath is swept on by it, and advanced a step forwards on its road to the rivulet, which will at last receive both it and the agent which moves it. At the same time, as these loose materials roll over the ground, they still further abrade and wear away the surface. The power of a gentle shower to move fine mud may be seen any rainy day either in a ploughed field or by a roadside: heavy storms, even in temperate climates, carry far coarser materials than most people are aware of, specially if the slope of the ground be steep. I recollect well enough having to leave a rock, which was affording me some small shelter during a thunderstorm in the centre of England, on account of the shower of stones which the rain washed over the edge, preferring the certainty of being wet through to the chance of having my head broken. In the tropics, where not only is the rainfall very large in amount, but also where an enormous quantity comes down in a very short time, the carrying and wearing effects become enormously increased.

We must also recollect that rain, besides acting as a carrier of loose matters, which it finds ready to hand, softens many rocks, such as Clay, and so renders them an easier prey to showers that come after.

The earth pillars of the Tyrol furnish an excellent instance of a case of denudation on a large scale, which can have been produced only by the action of rain. There is a very full account of them in Lyell's "Principles," 10th ed. vol. i. p. 335.

Chemical Action of Rain.—Rain also has the power of acting chemically on certain rocks, and carrying away some of their constituents in solution.

The rock most largely attacked in this way is Limestone. There is a gas popularly known as Carbonic Acid, but which is styled by chemists Carbon Dioxide (CO_2). A solution of Carbon Dioxide in water is supposed to form a weak acid, Carbonic Acid (H_2CO_3). Carbonic Acid, or a mixture of Carbonic Acid and water, has the power of dissolving Calcium Carbonate ($CaCO_3$), or Carbonate of Lime, as it is often called. Now Carbonate of Lime, it will be remembered, is the chief constituent of Limestone, and whenever water impregnated with Carbonic Acid comes in contact with Limestone, the Calcium Carbonate is dissolved out and carried away in solution. Almost all water on the earth's surface contains more or less Carbonic Acid;

Carbon Dioxide exists in small quantity in the air, and the rain, as it falls, takes up some, and so becomes mixed with Carbonic Acid; the same result is produced, when rain-water comes in contact with decaying vegetable matter, as it flows over the surface of the ground. Almost all surface water then has the power of attacking limestone, the dissolving away of that rock goes on incessantly, and the amount which is thus slowly and insensibly carried away becomes in time very considerable indeed. It is in this way that the caverns and underground watercourses, with which all Limestone countries abound, are formed. It is curious on taking up a good topographical map of certain districts to note that there is a line on reaching which all the streams suddenly cease. This line marks the boundary between a tract of Limestone and some other rock insoluble in water: over the latter the water runs in brooks, but on reaching the former it has by degrees dissolved away the rock and eaten out underground channels, into which it sinks and flows away out of sight. It is for this reason too that Limestone districts abound with funnel-shaped cavities, descending from the surface vertically into the rock, into which water sinks and disappears. They are often called Swallow Holes or Swallows. Wherever there was any little depression in which water could lodge, the bottom was eaten away lower and lower, and a pipe formed at last leading from the surface into an underground channel. Districts composed of very pure Limestone show bare rock up to the surface, because the rock is entirely soluble; when however the Limestone contains insoluble impurities, these remain behind, and give us the means of forming a rough estimate of how much has been removed. We have a good instance of this in the south of England. The surface of the Chalk Downs there is often covered, as shown in Fig. 7, with a red Clay full of Flints, known as Clay with Flints; the origin of which is as

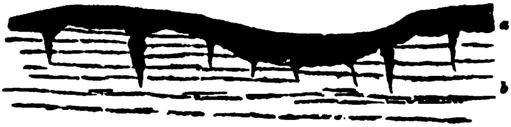

Fig. 7.—Clay with Flints resting on Chalk.

a. Clay with Flints. b. Chalk.

follows.* Chalk contains from 94 to 98 per cent. of Carbonate of Lime, mixed with from 2 to 6 per cent. of clayey and earthy matters, it has also embedded in it many nodules of Flint. The two last are practically insoluble, and therefore remain behind when the first is dissolved and carried away by percolating rain-water. The Clay with Flints often reaches a thickness of many feet, and testifies to the large extent to which the rock has been insensibly dissolved away.† In the same way many parts of Palestine‡ are thickly strewn with loose lumps of Flint, which have remained behind, while the Limestone, in which they were originally contained, has been carried off in solution. There is scarcely any of the manifold denuding processes, which is of such importance and so constantly brought before the notice of the geologist, as the dissolving away of Limestone by Carbonated Water.

In some cases, where Limestones contain a large admixture of siliceous matters, a sort of skeleton of the latter remains behind when the Carbonate of Lime is dissolved out, forming what is known as Rottenstone.

Another important decomposition effected by Carbonated Water is that of the Potash and Soda Felspars. The result is the production of Clay, and it is from this source that the materials of the clayey rocks have been in the first instance derived. We may take the decomposition of Orthoclase as an instance. That mineral is a double Trisilicate of Alumina and Potash: the result of its decomposition is Kaolin or China Clay. The composition of Kaolin seems from the investigation of chemists to be variable, but some forms of it certainly approach very nearly to a Hydrated Bisilicate of Alumina with the composition $2SiO_2,Al_2O_3+2H_2O$, or—

Silica	46·6
Alumina	39·5
Water	13·9

The following example of Kaolin comes under the above formula:—

Silica	46·32
Alumina	39·74
Iron Oxide	·27

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* Geology of parts of Middlesex, Herts, Bucks, Berks, and Surrey (Memoirs of the Geological Survey of England), p. 63.

† See also Bischoff, Chemical Geology, iii. 194.

‡ Dictionary of the Bible, Art. "Palestine."

Lime	·36
Magnesia	·44
Water	12·67

The result of the decomposition then has been to remove the whole of the Potash and a part of the Silica. Chemists are not agreed as to the form and manner in which these constituents are carried away. Some think that a soluble Silicate of Potash is formed. Others hold that the Silicate of Potash is decomposed, and that the Potash combines with Carbonic Acid and goes away as Carbonate of Potash, or partly as Carbonate and partly uncombined, and that the latter is taken up by plants. The resulting Silica may be carried away in solution and redeposited elsewhere. The occurrence of nodules of Opal, Chalcedony, and other forms of colloidal Silica in Kaolin, makes it very probable that some at least of the Silica is disposed of in this manner: but many Kaolins contain a much larger percentage of Silica than corresponds to the formula given above, and in their case it is likely that the whole of the free Silica is not removed, but remains either in a state of mechanical mixture, or combined in some different proportion with the Alumina.*

The formation of Kaolin goes on naturally to a large extent in many Granite districts, Cornwall for instance,† and deposits of the Clay are formed in hollows or flats, to which it has been carried by running water: such deposits contain grains of Quartz, imperfectly decomposed fragments of Felspar, scales of Mica, and other impurities, which are separated by washing.

The Oxygen of the air contained in rain-water also enables it to oxidise, or raise the degree of oxidation of some constituents of rocks. Thus, for instance, many rocks, when brought from a depth below the surface, where they are protected from the action of the air, are blue or grey, the colour being due to Carbonate of Protoxide of Iron. But the same rocks, when exposed to the atmosphere, are red, yellow, or brown, because the colouring matter has been converted into an anhydrous or some hydrated Sesquioxide.

Of the substances acted on chemically by rain-water the one most largely dissolved is Carbonate of Lime, partly because it is so readily soluble, and partly because Limestone is a rock so universally diffused. This being the case, it certainly seems strange that this salt can scarcely be detected at all in solution in sea-water; Sulphate of Lime and Magnesian Salts, which have doubtless come there in the same way as Carbonate of Lime, we do find in sensible quantities, but the last only in the smallest amount, or not at all. These apparently contradictory facts are capable of easy explanation, as we shall see, when we come to look at the formation of Calcareous rocks.

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* Zirkel, Petrographie, ii. 608; Naumann, Geognosie, i. 726; Bischoff, Chemical Geology, ii. 176; Wagner, Chemical Technology, p. 293.

† De la Beche, Report on the Geology of Cornwall, Devon, and West Somerset, p. 509.

Besides the substances mentioned, rain-water dissolves and carries away in solution others less common, as Rock Salt, Sulphate of Lime, Sulphate of Magnesia, and, under certain circumstances already mentioned, Silica.

2. Running Water.

Rivers as Carriers of Sediment.—As the portion of the rain that streams over the ground becomes gathered into definite channels, it brings into the brooks so formed the matters which it has swept mechanically along with it, or which it holds in solution, and the first function which running streams perform is to carry these on in their downward course.

In this way alone streams and rivers are most important auxiliaries in the work of denudation, they prevent accumulations of debris from acting as a shield against the action of denuding agents, and allow a bare surface to be always maintained for the latter to work upon.

We are apt at first sight to underestimate the carrying power of running waters, and to take notice only of the light matters which float on the surface, overlooking the far more important burden of fine mud they hold in suspension, the matters carried down in solution, and all they move forward by pushing them along the bottom. It is only when the amount of matter carried by rivers is subjected to actual measurement that we come to realise how large it really is. To take two instances, it has been determined that the Mississippi carries 7,459,267,200 cubic feet of sediment every year into the sea; and the Rhone 600,381,800: the first of these quantities would cover a square mile of ground to a depth of 268 feet.* We must also recollect that since the specific gravity of rocks lies between 2 and 3, they lose from a half to a third of their weight in water.

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* The student will do well to consult the admirable and exhaustive treatment of this subject, by Professor Geikie, in Jukes' Students' Manual of Geology, 3rd ed., pp. 420—429.

During floods the carrying power of rivers becomes very much increased, but I believe very few people are aware how enormous the increase is, unless actual instances of the work done by violent rushes of water happen to have come under their notice.* Here then are the details of a couple of actual cases.

C. Russell, 1877.

In 1866, twenty inches of rain—more than falls in many places in England in the course of a year—fell in Scinde in twenty-four hours, and the Mulleer River rose in consequence to an unusual height. The valley was crossed sixteen miles above Kurrachee by a bridge constructed of wrought-iron girders. The flood banked up wood and grass against the bridge, and at last threw it over, and one of the girders, weighing eighty tons, was carried two miles down the river and buried in sand. It is probable that in this case the accumulation of drift-wood served in some measure to buoy up the girder, but, even allowing for this, the transporting power of the current must have been astonishing.†

In 1864 a frightful flood was caused by the bursting of a reservoir above Sheffield. The rush of water was most violent, for it was estimated that 40,000 cubic feet passed along the narrower part of the valley per second. The official report states that 92,000 cubic yards of the embankment were swept away in less than half-an-hour, and mentions one stone weighing thirty tons which was moved; I saw myself a stone of about two tons, which I could identify by its shape as having formed part of a weir more than a hundred yards up the valley. Whole acres of meadow land were deeply buried beneath heaps of debris, consisting mainly of large angular blocks of rock, which the torrent had torn off from the banks as it rushed along.

Besides mechanically formed sediment rivers also carry away large quantities of matter in solution, which has been brought into them by rain or spring water, or dissolved out in their passage over soluble rocks. Thus the waters of the Nile contain 14 parts in 100,000, those of the Rhone

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* Mr. Hopkins states that the weight which a current of water can move increases as the *sixth power* of the velocity. Quart. Journ. Geol. Soc. of London, vol. viii., Presidential Address, p. 27.

† Quart. Journ. Geol. Soc. of London, vol. xxiv. p. 124.

17, those of the Main 24, and those of the Thames 40 of matter in solution.

Denudation wrought by Rivers directly. — But besides acting as the bearers of matter brought into them, streams take also a direct part in the work of denudation.

Running water has of itself little or no power to abrade rocks, except in so far as it may in some cases soften them and destroy their coherency by soaking into them; but the sediment, with which all streams are charged, enables them to effect a very large amount of destruction. This wears away the banks as it passes, and portions from time to time become undermined and topple over into the current, there to be ground fine and in the end swept away. The process may be seen going on even in rivers which flow peacefully through comparatively flat districts; and in more rugged tracts, where the stream runs at the foot of a lofty cliff, the amount brought down by each fall is proportionately increased. The undercutting will evidently go on faster if the base of the cliff consists of a rock softer than that on the summit, or if there be springs bursting out on its face.

Thus rivers are always performing a twofold work; they sweep along debris brought into them by rain, and this enables them to wear away their banks and beds, and to grind small the masses detached by its action, while it is itself at the same time still further comminuted, and rendered capable of being carried more easily and to longer distances.

The direct denuding action of rivers, like their carrying power, is of course vastly increased during floods. The Sheffield flood already mentioned furnished admirable proofs of this. Some small farmhouses, which stood across its path, were sliced in two, as neatly as if they had been cut through with a knife, one half carried away, and the other left standing. At sharp bends in the valley, where the water had impinged on projecting spurs of the bank, or where it had been driven into a recess, it had excavated in the solid sandstone rock large hollows, which any one, who was not aware of the circumstances of the case, would have supposed to be quarries.

Underground Streams.—We will next turn our attention to the water that circulates underground. In the case of rocks not acted upon chemically by rain, this finds its way down through cracks, or between the beds, or, in the case of a very open porous rock like unconsolidated sand, through the body of the rock itself. If its downward course is stopped by reaching a bed, through which it cannot force its way, it flows along the top of this bed, and escapes, when the bed comes to the surface, either in springs or by a general oozing out above the outbreak of the impervious stratum. Or it may be that the cracks by which it is descending become so narrow that friction against their sides seriously impedes its further progress; if in this case it meet with a wider fissure opening out upwards, it may be easier for it to be forced up this by hydraulic pressure than to continue to descend by gravity, and then it will mount up and issue as a spring.*

The natural pipes which feed springs of this class will not generally have a very large bore; but in the case of rocks which are chemically acted on by rain, there is scarcely any limit to the size of the underground channels which water makes for itself. Among the widely diffused rocks Limestone is the one most readily soluble, and in it accordingly are these underground watercourses most frequently met with: the water bursts out of them, not as a spring, but as a full-grown brook; and they sometimes swallow up, and after a time discharge again, the contents of good-sized rivers. It is scarcely necessary to give instances, but we may mention the Holy Well, at the town of that name in Flintshire, which was estimated by Pennant to discharge twenty-one tons of water in a minute.

The fable of

> Divine Alpheus, who by secret sluice
> Stole under seas to meet his Arethuse,†

was evidently based on a knowledge of the facts we have been describing, examples of which are extremely common in the calcareous districts of Greece.

Underground streams, provided their course is throughout downwards, may and do produce and convey mechanically formed sediment, just as rivers above ground, but the amount of it will obviously be small. Their principal share in the work of denudation is dissolving and carrying away in solution anything they can act upon chemically, and the amount removed in this way, so to speak invisibly, is very large indeed.

In volcanic districts, or where springs descend to a great depth, their waters become heated and impregnated with alkaline solutions, and are then able to dissolve Silica and other matters, which otherwise they would not be able to attack so easily. We have already seen however that under certain circumstances carbonated and acid waters are able to take up Silica at the surface. The increase of pressure at great depths also allows water to become more largely carbonated, and otherwise increases its dissolving power.

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* Geikie, Primer of Physical Geography, p. 46, Fig. 6.

† Comus.

Water accumulating below ground assists in another way in bringing about denudation of the surface. When large quantities of soluble rocks, such as Limestone or Rock Salt, have been dissolved away, the ground above falls in, and thus new channels are formed for rivers to run in, and carry on in their own way the wearing away of the surface. Thus many of the depressions, in which the lakes called "Meres" in Cheshire lie, have probably been formed by the sinking of ground beneath which thick masses of Rock Salt have been dissolved away;* and many of the "Dales" of Derbyshire and other Limestone districts have all the look of having been once caverns, the roofs of which have fallen in.†

3. Frost and Ice.

We now come to the denuding effects of water in its solid shape as ice.

If water be gradually cooled, it contracts as the temperature decreases till 39° Fahrenheit or 4° Centigrade is reached; it then begins to expand and continues expanding till it is converted into ice at 32° Fahrenheit, or 0° Centigrade.

Frozen Water.—In the process of expansion the efforts of the molecules to get further apart are so exceedingly powerful, that, if the water be shut up in a close vessel, they rend the latter open, even though it be formed of iron half an inch thick. Just the same result follows when water, which has soaked into the cracks and crevices of a rock, freezes. The expansive force tears the rock open, forces off pieces from it, and throws them down to be worked small by rain and other denuding agents.

The amount of ruin wrought in this way will evidently be very considerable. All rocks admit water, and, wherever frost occurs, it becomes one of the most powerful agents in their destruction.*

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* Ormerod, Quart. Journ. Geol. Soc., iv. 262.

† The Geology of North Derbyshire (Memoirs of the Geological Survey of England), p. 2.

Glaciers.—We have already seen how important a denuding agent water is, as it flows over the surface in its liquid state; in those cold regions, where water can exist only in a solid condition, the place of streams and rivers is taken by Ice Rivers or Glaciers, and these also do their share of denuding and transporting work. There is a certain line, called the limit of perpetual snow, whose height in the tropics is some 15,000 or 16,000 feet above the sea, and which gets lower and lower as we go northwards or southwards, till at last it comes down to the sea level. Above this line the temperature never rises for long together above the freezing point, and all the moisture which falls from the sky comes down, not in the shape of rain, but as snow. On a table-land, which rises above this limit, snow alone will fall; and, as very little of it is ever melted, layer after layer will be added, and the pile will be always growing in thickness. The snow thus heaped up is compacted into ice in various ways: the weight of the mass forces the air out from between the crevices of the snow flakes, and binds them together; and the water, which the thawing of the surface by the mid-day sun produces, trickles down into cracks and crevices, and becomes frozen there when night comes on. In this way in such situations enormous heaps of snow and ice arise. It would seem at first sight that under these circumstances the ice heap must increase in thickness every year, and that in consequence the table-land on which it rests will get higher and higher as time goes on; but this is not the case, snow-capped mountains and ice-clad table-lands retain the same elevation in spite of the constant additions to their covering, and there must therefore be some means by which ice is carried away from them as fast as it is being added above. Now if ice were a body rigid like glass, this increase in the height would take place wherever the ground rises above the snow line, and there would be scarcely any limit to the depth of the accumulations which would be formed in such situations. But though to look at it any one might well suppose that ice has as little power to change its shape, bend, or mould itself as glass, such is really far from being the case. Under a sufficient amount of pressure ice can be forced into new forms almost as readily as moist clay or dough, though the amount of pressure required to mould ice is far greater than suffices for the modelling of these evidently plastic materials, and the change of shape takes place in a totally different manner in the two cases.* Now suppose we laid clay on a table with a slight bulge upwards towards the middle, from which boards sloped down to the floor, and kept adding to it above, what would happen? For a time we might go on adding to the heap without producing any effect, but as we kept putting more and more on, the weight of the upper part would squeeze out some of the clay below, and at last force it over the edge of the table and down the boards, and as long as we kept heaping on above, clay would continue to be squeezed out below, and would slide in an unbroken sheet down the boards on to the floor. If there were grooves or hollows in the surface of the boards, the flow of clay would evidently take place chiefly along them.

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* See Geol. Mag., vol. vi. p. 491, for a good instance.

This is exactly what happens when a great heap of snow and ice has been piled up on a lofty table-land; the weight of the huge mass drives portions over the edges of the table-land and down its slopes; and, as the pressure from behind is kept up by the additions which are always being made to the pile at top, a continuous and steady flow is maintained. In high latitudes, where the snow line comes down to the sea level and the whole land is cased in ice, there is a discharge of the latter all along the coast line into the sea; in more temperate climates, where snow accumulates permanently only on very high ground, the ice drains off down the valleys in the form of long tongues, known as glaciers, which are really ice rivers, always sliding downwards, and whose motion, except that it is slower, differs in no respect from that of streams of liquid water. Glaciers descend far below the snow line, but sooner or later reach a level at which they can no longer remain in a frozen state, when they melt and become rivers.

The under surface of a glacier is just at the melting point, and the water derived from the thawing of the bottom layer of the ice, together with that which sinks down crevasses when the upper surface is melted by the mid-day sun, runs in a stream between the base of the glacier and the rock on which it rests, and issues, often in considerable body, from beneath the snout.

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* The student who wishes fully to understand how ice is able to manage this, must consult Tyndall, The Glaciers of the Alps; Lyell, Principles, vol. i. chap. xvi.; Canon Moseley, Proceedings of the Royal Society, xvii. 202; Croll, Phil. Mag., March, 1869, and September, 1870; Climate and Time, chaps. xxx. and xxxi.; also Nature, i. 116, iv. 447, v. 185, vi. 396.

The table-land on which snow accumulates is called the "gathering ground," and the parent mass of snow the "snowfield" or "névé."

Glaciers, like rivers, act as carriers of debris brought on to them. On the bare mountain slopes, which rise above the ice, atmospheric weathering goes on largely, and the loose matters thus produced roll down the hillsides and fall on to the surface of the ice. Thus long lines of dirt, stones, and large angular blocks of rock are always found fringing the edges of a glacier. These are called *Lateral Moraines.* When two valleys meet and their respective glaciers unite, the two inner lateral moraines run together into a heap of rubbish in the middle of the glacier and form what is called a *Medial Moraine.* In the case of a large glacier formed by the junction of many tributaries, there will be many of these medial moraines, so that in some cases the surface is so thickly strewn with dirt and rubbish, that the ice can scarcely be seen through it. All this burden is carried slowly forward by the downward movement of the glacier, and at last shot over the end, where it is piled up in a heap called a *Terminal Moraine.* The Terminal Moraine is constantly being worn and wasted by the stream which issues from beneath the snout of the glacier, and its materials are ground fine and swept down and go the way of other products of Atmospheric Denudation.

Fig. 8 is a somewhat diagrammatised view of a glacier formed by the junction of the ice streams of two valleys: the outer lateral moraines fringe the edges, a medial moraine is seen formed by the union of the two inner lateral moraines: at the extremity the lateral and medial moraines are being shot over to form a terminal moraine. A stream rushes out from an ice-cave beneath the glacier, which has cut its way through the terminal moraine, so that only small portions of the latter remain on each side. In the extreme distance we catch a glimpse of snow-clad hills forming part of the snowfield.*

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* The reader who wishes to have in a few words a graphic description of glacier regions, should turn to Professor Geikie's Primer of Physical Geography, p. 75. For details, see the works of Agassiz, Charpentier, J. Forbes, Tyndall, and the publications of the Alpine Club; also the "Report on Ice as an Agent of Geological Change," Reports of British Association, 1869, p. 171.

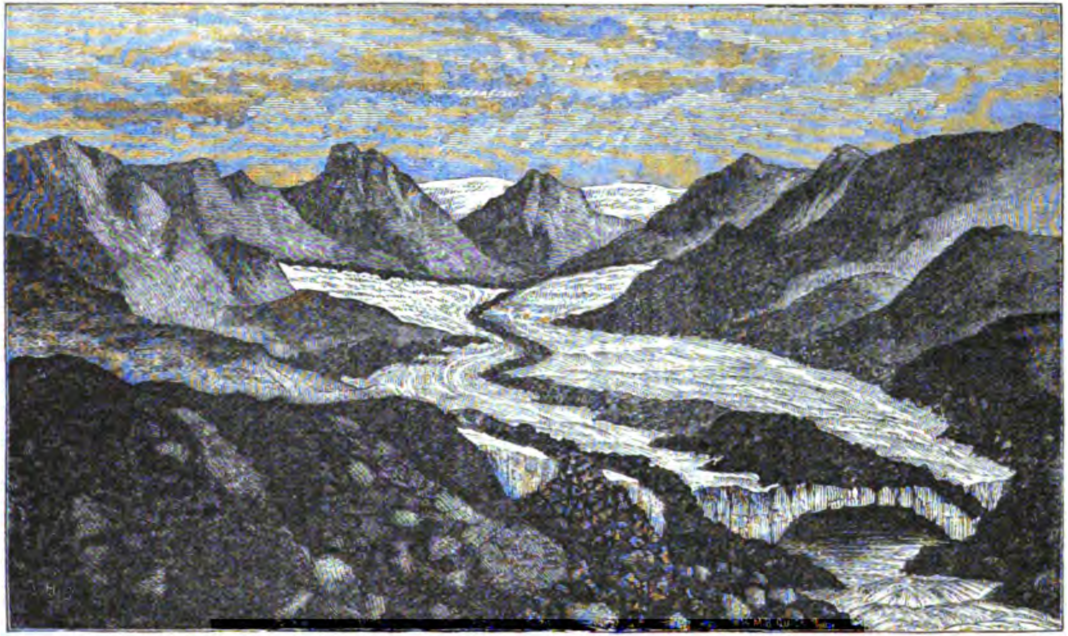

Fig. 8.—Glacier with Lateral, Medial, and Terminal Moraines.

As rivers abrade their banks and beds by the aid of the sediment they carry along, so glaciers wear away the bottoms and sides of the valleys along which they flow. Stones fall through the fissures or crevasses which traverse the ice, or are picked up from the bed of the glacier, and get firmly frozen into its base. The under surface is thus converted into a great rasp, which grinds the rocks over which the glacier passes, and wears them down into the finest and most impalpable mud. The stream below the glacier carries this on, and rushes out from beneath the end largely charged with mud ground so fine as to be easily carried to long distances. The great network of the tributaries of the Rhine for instance is formed of streams draining the northern flank of the Swiss Alps, the fine glacial mud brought down by them is carried on by the river, and out of its settlings the flat lands of Holland have been in great measure formed.

Continental Ice-sheets.—In Arctic or Antarctic regions, where the conditions for the accumulation of large masses of snow and ice are present, the ice is not confined to the valleys, but the whole land becomes cased in a widespread sheet of it, which wraps everything in one unbroken covering from the highest ground down to the sea level. The best known case of this sort is that of Greenland: the interior of this country, wherever an attempt has been made to penetrate into it, has been found to be buried in ice, and it is probable that the ice-sheet stretches without break over the whole land. In some parts the frozen mass reaches quite down to the coast, and terminates in an abrupt wall, not uncommonly from one to three thousand feet high, and sixty miles or more in length. Elsewhere strings of hills stand up, like islands, between the interior ice and the sea, and in the valleys and fiords, which separate these detached masses of bare land, the ice passes out to sea in great glaciers.*

Just in the same way as glaciers, masses of continental ice are always slowly moving from the interior to the coast, whence they continue their motion over the sea bottom till the water is deep enough to buoy the end up: hugh masses then break off and float away as icebergs. Icebergs are also formed by portions, which tumble into the water from the wall in which the ice-sheet sometimes terminates. Just as in the case of glaciers too continental ice-sheets grind the surface of the ground, over which they pass, into fine mud, and discharge large quantities of it by subglacial streams directly into the sea. But it also seems likely that huge ice masses, such as we are now considering, will grind and tear up the ground underneath them to a much larger extent than even the largest valley glacier can do, and that there will be thus formed beneath them a great mass of stones and dirt. To this the name of Moraine Profonde or Grundmorane is given. This pell-mell assemblage will be pushed to and fro by the moving ice, and if it be driven into a valley or sheltered recess, the ice-sheet may ride over it, and disturb it no further, and there it may remain, and if any improvement in climate cause the ice to disappear, it will furnish a proof of the former presence of an ice-sheet long after the latter has ceased to exist.*

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* See the works of Dr. Kane and Dr. Hayes; Dr. Brown, Quart. Journ. Geological Soc. of London, xxvi. 671; Rink, Journal of Royal Geographical Society, xxiii. 145. For the Antarctic Regions, see Sir J. Ross's Voyages.

If any peaks of bare rock rise above the surface of a sheet of continental ice, moraines will be formed on the latter, just as they are formed on glaciers, and carried down to the coast. Icebergs bear away portions of this moraine matter, and also stones from the moraine profonde frozen into their base, and drop their burden as they melt. In this way rubbish, and large unrounded blocks of rock, are deposited on the sea bottom far away from the source from which they were derived.

Coast Ice.—Ice also does important work as a carrier of denuded matter, in the shape of coast ice and ground ice. In high latitudes it often happens, that, from the melting of snow on the shore, the water adjoining the land becomes freshened far enough to allow of its freezing at a higher temperature than the body of the sea, and a belt of ice, known as coast ice or "the ice foot," is formed along the shore. On to this fringe of ice debris rolls down from the land, and shingle gets frozen into its under surface. The coast ice is lifted and at last detached by the rise and fall of the tide, and portions of it with their load of detritus float away, and drop what they carry as they melt.

Ground Ice.—Ice known as "ground ice" or "anchor ice" forms sometimes, in a way not perfectly understood, at the bottoms of lakes and rivers while the rest of the water remains unfrozen. Pebbles and other loose matters are frozen into the under surface of this sort of ice, and lifted by it and floated away when it rises to the surface.

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* J. Geikie, The Great Ice Age, chaps. vi. and vii.

4.—ACTION OF WIND.

The share which wind takes in the work of denudation, though not very large, ought not to be entirely overlooked. Its effects are best seen in those isolated blocks or pinnacles which often rise from the surface of a country composed of coarse sandstone. These are very frequently undercut or worn away below, taking the shape of anvils or one-legged tables—

> Shapes
> The sport of nature, aided by blind chance,
> Rudely to mock the toiling works of man.*

In these cases we find the surrounding ground strewn with coarse sand produced by the decomposition of the rock below. This sand the wind drives against anything that stands up above the surface and grinds it away, but as the wind can lift the sand only a short distance from the ground, the wearing is confined to the lower portion of the obstacles. Fig. 9 is an instance of one of these undercut rocks: in this case probably the process has been helped by the coping-stone being harder than the beds below, but plenty of cases occur where pillars of rock of equal hardness throughout are hollowed out underneath in exactly the same way. Similar forms are very common in Granite.

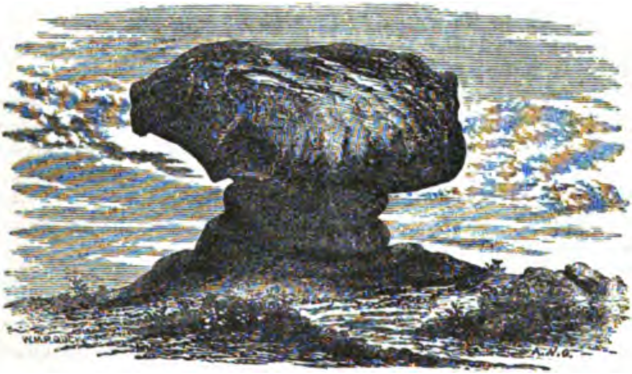

Fig. 9.—UNDERCUT TABLE OF GRITSTONE.

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* Wordsworth.

Rocks weathered in this way are frequently mistaken for "Druidical Remains."

In deserts, and other large sandy tracts, the drifting of sand by the winds grinds and wears rocks that stand in its way, and produces very remarkable polished surfaces and scratches upon them, not unlike those due to the action of moving ice.

By processes like these no inconsiderable amount of rock is worn away.

Denudation of this sort is sometimes called Æolian.

Wind also acts as a transporting agent; sand and dust, and any loose matters produced by the weathering of rocks, are swept by it into running water or the sea: but perhaps the most important work it does in this way is by transporting the light ashes thrown up by volcanoes; these are carried by it to vast distances; if they fall on the land, they are ready to be swept further on by rain and rivers; or they may fall directly into the sea: in either case they furnish materials for subaqueous strata.

Wind also aids the sea and other large bodies of water in the work of denudation by causing waves and unusually high tides. In this way they are enabled to act more energetically in the destruction of their coasts and banks, and the rush back of the pounded-up water, when the gale abates, sweeps before it with more than usual force the stuff which the storm has brought down.

5.—ORGANIC DENUDING AGENTS.

The help given by plants and animals towards denudation, though not very important, calls for a passing notice.

Burrowing animals, such as rabbits and moles, undermine the ground, give passage to rain, and so weaken the surface and render it an easier prey to other denuding forces. The matter they throw out is ready to be carried away by rain: in this respect even so insignificant a creature as the earthworm has been thought worthy of being noticed by geologists. Marine boring-shells and land-snails bring about the destruction of Limestone to a small but appreciable extent.

Trees destroy rocks mechanically by forcing down their roots into crevices and so splitting off portions: but plants do their most important denuding work indirectly; by their decay they furnish Carbonic Acid to water and thus enable it to dissolve Limestone. Professor Ansted mentions cases of holes drilled in this way to great depths, and sometimes right through blocks of Limestone, each hole containing the stem of a plant which by supplying Carbonic Acid to water had been able to work through the rock as effectually as a boring-drill.

GENERAL VIEW OF SUBAERIAL DENUDATION.

Such then are the main subaërial denuding agencies, and the ways in which they each individually do their work; let us next see what is the result of the joint action of all.

The first step in the process of subaërial denudation is the formation of soil.

Formation of Soil.—Actual bare rock is a thing not often seen at the surface; in a vast majority of cases what we first come to on breaking up the ground is a layer of soil. This is almost universally the case in flat countries, very generally so in hilly ones, and it is only in mountainous tracts that we find any widespread exceptions to the rule.* Now it is in most cases easy to see that this coating of soil does not consist of matter brought from a distance and spread over the solid rock beneath, but that it is nothing more than the upper portion of that rock itself, broken up and converted into sand, clay, or some other incoherent material. Various subaërial denuding agents have worked together to produce this result. Rain has softened and in some cases decomposed chemically the constituent minerals of the rock; frost has shivered it; the heat of the sun and other atmospheric agencies have dried, cracked, and pulverised parts of it: the roots of trees and perhaps burrowing animals have had some share in breaking it up; by these, and such like forces, any exposed surface of rock is incessantly being attacked until a portion of it is converted into loose soil. The natural planes of division, known as joints and cleavage, by which rocks are traversed, aid materially in this work of destruction. They allow of the percolation of water into the body of the rocks, and are planes of weakness along which fracture is readily produced.

On exposed mountainous countries the light matters thus formed are washed away by rain, or roll down the hillsides by their own weight as fast as they arise, and therefore in such situations the rock is constantly kept bare in spite of the attempts made by subaërial denuding agents to bury it in its own debris: in countries less hilly, and with a smaller rainfall, the process of removal goes on to a smaller extent; while in flat countries, where the fall of the ground is small, and the carrying power of water running over it is little or nothing, soil forms faster than it can be carried away, and the solid rock is everywhere deeply buried in its own ruins.

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* This statement is not strictly true of limestone countries, which show always a tendency to a bare rocky surface, because the carbonate of lime is dissolved by the rain-water and carried away in solution.

These accumulations of rain-borne decomposed rock go by the general term of "Rain-wash;" they may be distinguished (1) by their materials being strictly local in their origin, (2) by their stones, if they contain any, being not water-worn, but angular, or at most showing only so much rounding as might be produced by the chemical dissolution of their angles and edges. Deposits of rain-wash of various kinds occur in the south of England.*

Deposits of this class are also very largely developed in Spain, in the flatter parts of which we may travel for hundreds of miles without seeing a bit of rock except in the deepest railway cuttings; so that from a general point of view the country may be said to present only two physical features, broad plains of rain-wash and mountainous Sierras. The causes of this are twofold: the large and violent rain-fall, and the great extremes of temperature which often prevail, give rise to rock-disintegration on a large scale, and the plateau-like form of the ground prevents the debris so formed from being carried away.

The surface disintegration of rocks is nowhere better shown than in the case of Granite and some Traps. In Granite, this is due mainly to the atmospheric decomposition of the Felspar, and in this way the rock is often reduced to a mass of loose fragments, which can be shovelled out with a spade to a very considerable depth.† A large tract of country round Madrid, which is coloured on some geological maps as Diluvium, is covered by decomposed Granite, in which it is easy to pick out bits of the rock only partially disintegrated. In the same way some diorites weather down to loose earth, in which are embedded concretionary nodules that have been hard enough to resist decomposition; and the whole has so exactly the look of the accumulation of sand and boulders formed by a mountain torrent, that it might well be mistaken for a mass of water-worn materials.

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* See Goodwin Austin, Quart. Journ. of the Geol. Soc., vi. 94, vii. 121; Foster and Topley, ditto, xxi. 446.

† See De la Beche, Geological Observer, pp. 3, 4.

Removal of Soil from higher to lower Levels.—We must now advance a step further; only a portion of the disintegrated rock remains to form soil: in some cases we have seen it is swept away as fast as it forms, and, even when the rate of formation is greater than that of removal, some part of the loose matter is constantly moving onwards. Sooner or later the products of surface weathering find their way into a brook, and are swept forward by it, either in suspension or by rolling along the bottom, till the brook joins a larger stream, along which they travel till the stream falls into a river, and along this they continue their course till the river is lost in the sea.

At the same time these transported materials enable the water of the streams, which by themselves have little or no abrading power, to wear and grind the banks between which they flow, and thus to add to the amount already being carried downwards by them.

The sum total of transported matter is also swollen by salts and other substances dissolved by rain in its course over the ground, brought up from below in solution by springs, or taken up by the waters of the river itself in its passage over soluble rocks. The amount of these chemically dissolved substances is far from inconsiderable: thus Professor Ramsay tells us that the Thames carries every year into the sea 33,497 tons of matter (chiefly Carbonate of Lime) in solution; and this, if precipitated and compressed into Limestone, would form a bed a yard thick and more than seven acres in extent.

The above are the principal steps in the process by which water in its liquid state transports the products of subaërial denudation continually from higher to lower levels. The share which it contributes to the work, in its solid shape as ice, falls next to be considered. We have seen that the streams which issue from beneath the snouts of glaciers are largely charged with sediment already ground so fine that it is at once carried forwards. The coarser matters shot over to form the terminal moraine are attacked by various subaërial denuding agents, in the end ground fine enough to be moved, and then are carried away.

Where glaciers or masses of continental ice come down to the sea level, the streams beneath them discharge directly into the sea large quantities of finely comminuted mud; and the icebergs which break off from them carry away coarse materials and large unrounded blocks of rocks, and deposit them far away from the spots from which they were derived.

In a word, the surface of the ground is constantly acted on by a number of agencies, which all work together to wear and break it up: the loose matters so produced are carried downwards, and at the same time added to, by moving water either in a liquid or a solid state, till they at last come to rest at the bottom of large bodies of still water. This chain of events, all intimately connected with one another, constitutes the process of subaërial denudation.

6.—Marine Denudation.

The sea to a very large extent only finishes work begun for it by subaërial denuding agents.

The coarser stuff brought into it by rivers is tossed to and fro by the tides, till it is ground fine enough to allow of its being swept away altogether. In the case of a coast bounded by cliffs, the expansion of frozen water, the undermining caused by the outbreak of springs, or the unequal yielding to the weather of beds of different hardness, and other similar causes, break off and throw down large masses, and the sea completes the work by grinding these into mud, shingle, or sand, and then by the aid of tides and currents sweeping them away.

But the sea may also claim a certain amount of the denuding work which it effects as entirely its own. In the same way as the sediment carried by running waters enables them to grind away their banks, the sea uses the boulders and shingle of the beach as instruments for the destruction of its cliffy shores. Waves, rolling in from open ocean spaces and driven forward by gales of wind, have force enough to lift and hurl against anything that comes in their way enormous masses. By this means the loose blocks, that fringe in heaps rocky shores, are dashed with fearful violence against the cliffs, and by this incessant pounding and battering fresh portions are from time to time brought down, to be used in their turn as instruments for further destruction.

Thus the fact that the coast rocks are hard so far from protecting them from the encroachments of the sea, makes them in some measure a more certain prey to its wearing action, for the harder the rock is, the more destructive will be the ammunition furnished by its ruins. Where the coast is composed of soft rocks, it is eaten into all the more easily; its destruction is incessant, and the advance of the sea becomes rapid enough to be obvious even to the most casual observer.

It must be noted that the destructive action of the sea is confined almost entirely to the belt between high and low water mark. Within that space the rise and fall of the tides and the force of the breakers grind down any loose matter exposed to their action. These agencies however cease to have any effect on a bottom covered by a moderate depth of water, and hence *very nearly all the denuding work of the sea is Coast Denudation.* The drifting of rough sediment over the bottom by under-currents may produce some abrasion, but its amount cannot be very large.*

Relative Importance of Subaerial and Marine Denudation.—We may here note that marine denuding agents, such for instance as the beating of the waves on an exposed rocky coast, are far more striking and appeal far more forcibly to the imagination than the slow and almost insensible action of subaerial denuding forces. The latter, partly because they are so common, partly because their action is so gentle, and partly because they operate so slowly that their results are inappreciable unless they are very carefully measured or observed over a long period of time, are apt to be overlooked, and indeed were for a long time, if not actually overlooked, yet denied their true importance by geologists. It is now however very generally recognised that they perform by far the larger part of the denudation that is going on before our eyes, and they have at last had their true place granted them in the roll of denuding forces, a place to which Hutton long ago pointed out that they were entitled.

It seems almost past belief that the importance of subaerial denudation should have been so long overlooked, and that truths so simple and apparently so self-evident as those, of which we have just given an abstract, should not have forced themselves on the notice of geologists from the very first birth of the science. The explanation however is easy enough, and furnishes so useful a lesson to the would-be cultivator, not only of geology, but of any other science, that it is worth calling attention to it. Men failed to see these obvious truths simply because they did not look for them; because, instead of going forth and marking Nature, they amused themselves with weaving ingenious conceits in arm-chairs at home. Hutton was the first clearly to enunciate the laws of denudation, which he had learned by observation; the summary of one of his chapters is worth quoting: "Whether we examine the mountain or the plain; whether we consider the degradation of rocks or of the softer strata of the earth; whether we contemplate Nature and the operation of time upon the shores of the sea or in the middle of the continent, in fertile countries or in barren deserts, we shall find the evidence of a general dissolution on the surface of the earth, and of decay among the hard and solid bodies of the globe." Playfair puts it more tersely thus: "The consequence of so many minute, but indefatigable agents, all working together, and having *gravity* in their favour, is a system of universal decay and degradation, which may be traced over the whole surface of the land, from the mountain-top to the sea-shore."

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* For Marine Denudation, see Lyell's Principles, vol. i. chaps. xx. and xxi.; De la Beche's Geological Observer, sec. v.; Geikie, The Scenery of Scotland viewed in connection with its Physical Geology, chap. iii.

Another useful lesson may be learned from this bit of the history of Geology. It is now nearly eighty years since the Theory of the Earth was published, and it is only quite lately that geologists have come to recognise the truth of its teaching. So slow are men, even when the right road is pointed out to them, to leave a groove which they have been for a long time following.*

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* In connection with the subject of Denudation, the student will do well to read, Theory of the Earth, Part I. chap. i. sec. iv., Part II. chaps. iii. to vii.; Playfair's Illustrations, sec. iii.; Scrope's Volcanoes of Central France, 2nd ed., chap. ix.; Ramsay, The Physical Geography and Geology of England and Wales; A. Geikie, The Scenery and Geology of Scotland; A Streng, Über den Kreislauf der Stoffe in der Natur, Leonhard and Geinitz Jahrbuch, 1873, p. 33.

CHAPTER IV.

WHAT BECOMES OF THE WASTE PRODUCED AND CARRIED OFF BY DENUDATION.—THE METHOD OF FORMATION OF BEDDED ROCKS, AND SOME STRUCTURES IMPRESSED ON THEM AFTER THEIR FORMATION.

> The Rhone by Leman's waters washed,
> When mingled and yet separate appears
> The river from the lake, all bluely dashed
> Through the serene and placid glassy deep,
> That fain would lull her river-child to sleep.
>
> BYRON.

SECTION I.—MATTER MECHANICALLY CARRIED.

HAVING now passed in review the various agencies which at all times and in all places are at work breaking up the surface of the earth, and having convinced ourselves that the larger part of the waste which results from their action finds its way sooner or later into running waters, and is carried on by them in their downward course, our next task is to inquire what happens to the matters thus swept away when the streams which bear them along are lost in bodies of still water,. such as the sea or a large lake; and we will begin with the mechanically transported matters, those namely which are carried in suspension, and those which are swept along the bottom.

When the velocity of the stream is by degrees checked, and at last destroyed altogether, it can no longer bear along its burden, the stuff that has been rolled along the bottom comes to rest, and the sediment held in suspension sinks down.

But the suspended matters will not fall all together: there will generally be some of them heavier than others, some coarse and others more finely divided. Long after the current has ceased to be able to hold up the heavy and coarse part, it may retain velocity enough to carry forward the light and more finely divided, and the latter will travel much farther than the former from the mouth of the river before they reach the bottom.

Arrangement of Mechanical Deposits according to Size and Weight.—In any large body of water, then, fed by running streams, we should find deposits on the bottom arranged somewhat in the following order.

Fringing the coast, and especially facing the mouths of the rivers, there will be a belt of banks of coarse pebbly materials. In the case of lakes or tideless seas these may stretch out for a considerable distance, for when the water has been shallowed for some way out by the formation of a bank of shingle, pebbles may be rolled on in the shallow water on the top of the bank and shot over the end, and the front in this way be continually pushed forward. Along the shore of the open ocean no broad accumulation of shingle can take place, for the pebbles are always being ground fine, and swept out to sea by the rise and fall of the tides and the beating of the breakers.

When these shingle-banks can be formed, they will evidently be thickest on the shore side, and thin away in a wedge-shaped form as we advance into deeper water.

Beyond the shingle-banks, and resting on their thin edges, there will be other banks of a similar shape, but formed of materials a little less coarse: and because the components of these can be borne rather further than the coarsest shingle before they come to rest, these banks will not thin away quite so rapidly, and will form wedges with angles more acute than those of the banks next the shore.

In this way as we leave the shore we shall find the deposits becoming less and less coarse, and arranged in wedges getting more and more acute, till at last their upper and under surfaces become approximately parallel, and they take the shape of beds or strata.

The lightest and most finely divided matters will sink very slowly through the water and travel far before they reach the bottom, and will come to rest in layers or laminæ, which keep nearly the same thickness over large areas.

Arrangement of Mechanical Deposits according to Mineral Composition.—Besides these differences in arrangement there will also be a difference in the mineral composition of the deposits fringing the shore and those remote from it.

The sediment carried down mechanically by running water consists mainly of two kinds, sandy or siliceous, and clayey or argillaceous. Now quartz, of which sand is composed, is very hard, and will stand a great deal of wear and tear before it gets ground fine; hence the coarser deposits will be mainly sandy. Clay, on the other hand, is soft, and easily worn down into the finest impalpable mud; hence the finer deposits will be mainly clayey.

Therefore we shall find, as a rule, that near the shore *wedge-shaped banks of coarse, sandy* materials prevail, while further out *regularly bedded layers of fine clay* cover the bottom.

This order will not be without interruption, because during floods the coarser materials will be carried further out than usual, and so wedges of sand will come to be interleaved among the evenly bedded clays; and in the same way, when the rivers are low, clayey deposits will be formed in the sandy region: still upon the whole the general arrangement of the deposits will be such as has been described.

Finally, if the ocean be large enough, there will be a limit, beyond which no river-borne sediment will be carried, and no mechanical deposit formed on the sea bed. These regions however, as we shall see further on, will not be without deposits, for in them marine animals build up great masses of pure Limestone.

General Arrangement of Mechanical Deposits.— In Fig. 10 an attempt is made to show diagrammatically the arrangement of mechanically formed deposits. The dark part is the solid rock forming the land and the sea bed; the straight line the sea level. Looking at the lower and therefore first-formed accumulations of sediment, we see close to the shore a bank of large pebbles with a steep face seawards: beyond this there follow other banks, the first of pebbles not so large as on the bank nearest the shore, the next of coarse sand, the next of finer sand, and so on: and the seaward faces of all these banks get less steep as we leave the shore. Beyond the finer mud stretches out in thin layers, becoming more and more nearly horizontal as we get out to sea. After these beds had been laid down, the streams ceased for a while to have the power to carry coarse sediment, and could not bear even fine mud as far as before: consequently the latter sank down nearer the shore, filling up the hollows between the banks, and levelling over their uneven surface. Subsequently coarse matters were again brought into the water, and a range of banks similar to those in the lower part of the section were piled up on the top of the layers of mud, while finer deposits again began to accumulate in the remoter parts of the ocean. In the diagram the transitions are, for the sake of distinctness, made abrupt; but in Nature the passage from shingle to sand, and from sand to mud, would be much more gradual, and, as the material grew finer, almost insensible.

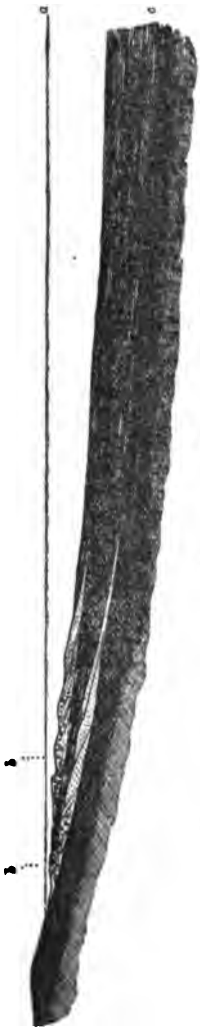

Fig. 10.—Distribution of Mechanical Deposits on the Sea-bottom.

a. Sea Level. b. Wedge-shaped Banks of Shingle and Sand. c. Regularly bedded Clay.

In the crust of the earth we meet with rocks which, except that they are harder and bound more firmly together, bear the closest resemblance to the accumulations that have just been described. Conglomerates are composed of exactly the same materials as the shingle of the beach and littoral zone; Sandstones of all degrees of coarseness find a parallel in submarine sandbanks; there are sandy shales, which are mixtures of fine sand and mud; and the finely laminated argillaceous shale corresponds exactly to the evenly bedded deposits of small silt and mud. And among these rocks we find also just the same arrangement as has been described in the last few pages. In the great masses of pebbly Sandstone, as in shingle-banks, the pebbles are found to grow smaller and smaller as we trace the rock in a certain direction, and at last disappear altogether, so that the bed passes insensibly into a rough gritstone, this again still further on merges into a finer Sandstone, and perhaps at last is found to tail out altogether in a wedge-shaped form, and to be replaced by deposits of more regularly bedded hardened sandy mud, and these in turn shade off into more purely clayey mud.* We also find alternations of sandy and clayey rocks, corresponding to the alternations of banks of sand with deposits of mud, which are now being produced by variations in the transporting power of currents.

Some substances remain suspended in water not so much on account of their low specific gravity as in virtue of their form. One of the commonest of these is Mica. The thin laminæ, into which this mineral splits, present a broad surface to the water and give rise to an amount of resistance to sinking very large in comparison with their weight; hence they settle down very slowly and regularly. In this way the surfaces of the beds of regularly stratified deposits are thickly flecked over with little spangles of this mineral. Sandstones and shales of this character are very common, and are called *Micaceous Sandstones* and *Shales*. That Mica does behave in the way described is found out in the washing of China Clay: owing to the way in which the water holds up its thin plates, it is the most difficult impurity to get rid of.

We will now examine a little more in detail the nature and characteristics of deposits formed near the shore.

Horizontal Growth of Coarse Deposits.—In a sea, which deepens rapidly, coarse deposits will be confined to a belt fringing the coast: but in a large area of shallow water they may extend over a much wider space: for, as soon as a belt of banks such as we have described has formed along the shore, the water above is rendered shallow enough to allow of coarse materials being rolled over their tops, and shot over their seaward faces; and in this way the front of the bank will be always moving from the shore, and the deposit extended as far as the water continues sufficiently shallow.

Vertical Growth of Coarse Deposits.—But we have yet to account for the existence of deposits, evidently formed in shallow water, and yet of great thickness. For instance in the Coalfield of South Wales rocks certainly subaqueous, but none of which can have been deposited in deep water, are piled one on the other to a thickness of ten thousand feet.

We shall see by-and-by that the surface of the globe is never at rest, that portions are rising and others sinking, and that these changes of level have been going on throughout all past time. Now suppose the bed of a shallow sea to be sinking, say at the rate of a foot in a century, and also that in the same time one foot of sediment is laid down all over the bottom; then, since the accumulation of sediment fills up the water at exactly the same rate as the sinking would deepen it if no deposition were going on, it is clear that the depth will always remain the same, and that the conditions necessary for the accumulation of shallow-water deposits will always be preserved; and with such an adjustment any thickness whatever of such deposits may be obtained.

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* For an instance, see Quart. Journ. Geol. Soc., xx. 265—267.

Wherever then we find a great thickness of beds, which must have been formed in shallow water, we know at once that during their deposition the sea bed must have been sinking at about the same rate as they were accumulating.

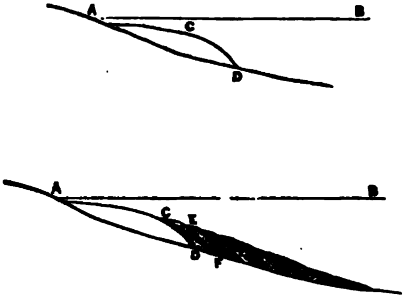

Fig. 11. FORMATION OF CURRENT BEDDING.

Drift or Current Bedding.—We may now look a little more closely at the way in which the materials of the banks of coarse sediment are arranged. In Fig. 11, *AB* is the surface of the water, and *CD* the front of one of these banks in course of formation. From *A* to *C* the water is shallow enough to allow the current to retain velocity sufficient to roll sand or pebbles along the bottom, but in the deep water beyond *C* this velocity becomes suddenly checked and their further progress arrested. The coarse matters are therefore shot over the edge of the bank, and arrange themselves in a little sloping layer, *CDEF:* by this means the extent of shallow water will be a little increased, and another sloping layer added above *CD*.

And so the process goes on, till in the end a bank is formed *made up of thin sloping layers all dipping in the direction in which the current is moving.*

If a current with a different direction pass over the same spot, another bank will be piled up, composed like the first of thin sloping layers, but with its layers dipping towards a different quarter.

By a repetition of this process we shall obtain a deposit made up of wedge-shaped beds, each of which is traversed by smaller planes of division crossing the main lines of bedding obliquely.

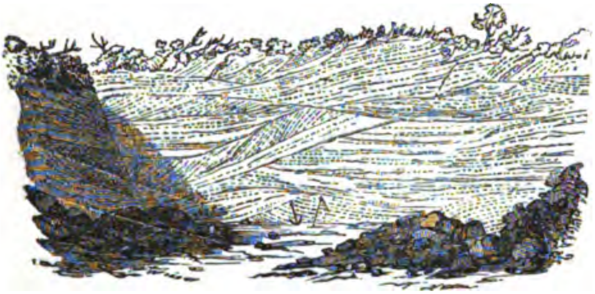
Fig. 12.—Quarry in Current-bedded Rock.

Such a structure is called False-bedding, Cross-bedding, Current-bedding, or Drift-bedding; an example of it is given in Fig. 12. Rock possessing this structure is sometimes called "Eddy Rock" by quarrymen and well-sinkers.

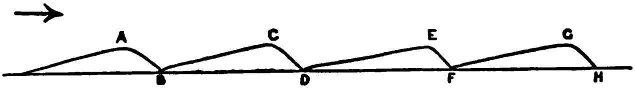

Fig. 13 (*a*).

Ripple-drift.—Let us next consider what will happen on a sea-bottom on which a current is forming ripple-marks. The shape of the bottom is such as is shown in Fig. 13*a*, the arrow being the direction of the current, and each ripple having a long gentle slope on the side from which the current comes, and a steeper slope on the opposite side. If no sediment is being brought into the water, the current will roll sand up each gentle slope, and the latter will fall down over the steep slopes, and the only thing that will happen will be a general movement of the ripples in the direction of the arrow. But if sand be sinking through the water, it will, as it falls on the gentle slopes, be rolled up them and over their edge, and fall down in a layer over each of the steep fronts, *AB*, *CD*, *EF*, as in Fig. 13*b*. In this way the steep fronts will always be added to, till at last the old surface, *ABCDEFG*, will be effaced by the filling in of the hollows *ABC*, *CDE*, *EFG*, and a new rippled marked surface, *aAbCcEd*, formed above it, Fig. 13*c*. By continuing this we shall at last arrive at a rock like that shown in Fig. 13*d*. This structure is called "Ripple-drift."* Both Current-bedding and Ripple-drift are common in rocks which have been formed in shallow water: indeed it is scarcely possible to find a sandstone which does not show one or the other to a greater or less degree.

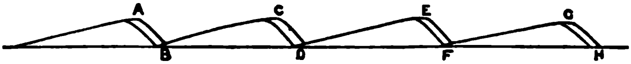

Fig. 13 (*b*).

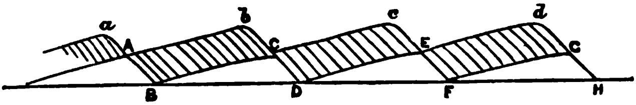

Fig. 13 (*c*).

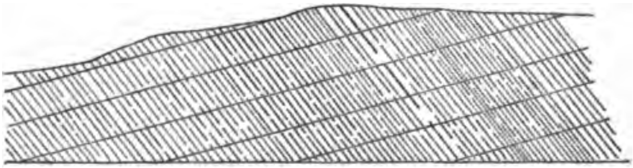

Fig. 13 (*d*).

Contemporaneous Erosion.—Another cause of great irregularity in the bedding of shallow water deposits is the erosion of part of one bed by a current before the bed next above was laid down. A good case is shown in Fig. 14. Here the evenly bedded mud in the lower part of the section was once continuous throughout: but a hollow has been cut out in it by a current or river, and then sand rolled in and the hollow filled up with it: mud and sand are now both compacted into hard Shale and Sandstone. Cases of this sort are of very common occurrence in beds of Coal, when they are known as "Rock Faults" or "Horses." What is now Coal was originally a sort of peat-bog: by some change in physical geography a river has been turned across the bog and cut out in it a channel, and this has afterwards been filled in by drifted sand now hardened into Sandstone.*

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* See H. C. Sorby, Edinburgh New Philosophical Journal, New Series, vols. iii. p. 112, iv. p. 317, v. p. 275, vii. p. 226.

Ripple-marks, Rain-drops, Sun-cracks, and Animal Tracks.—We may here notice one or two appearances which present themselves alike in the deposits now forming on the shores of seas or lakes, and in rocks which were laid down long ago under similar circumstances. If we walk over a sandy beach laid dry by the fall of the tide, we often find the surface of the sand marked with a rippled pattern, like that produced on water ruffled with a gentle wind. This is known as "Ripple" or "Current-mark," and is due to a wavelike motion set up in the semi-fluid wet sand of the sea-bottom by currents passing over it. A shower of rain also pits over the sand with little hollows; and, when the wet ground is dried by the sun, it cracks and opens into small fissures; also the beach is often thickly stamped over with burrows and coil-shaped ejections of worms and the tracks of crustaceans and other marine animals. Birds and animals frequenting the margin of water also leave their footprints on the soft beach. Similar markings are formed on the muddy bottoms of lakes, when the water has sunk below its usual level through long drought.

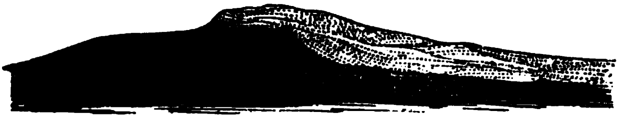

Fig. 14.—CONTEMPORANEOUS EROSION.

a Shale which has been partly cut away.
b Sandstone filling up the hollow in (*a*).

Ripple-marks and some of the animal tracks can be formed under water, as well as on spots alternately dry and overflowed: they will generally however indicate water of no great depth, because the currents, which cause the former, are commoner and more powerful in shallow than in deep water.*

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* See the Geology of the South Staffordshire Coalfield (Memoirs of the Geological Survey), pp. 45, 51; Buddle, Transactions Geological Society, Second Series, vi. 215; and for erosion, contemporaneous with the formation of a set of beds, on a larger scale, Quart. Journ. Geological Society, vol. xvii. p. 457.

Rain-drops and sun-cracks however can arise only on surfaces dry, but still soft from recent submergence. They may occur between tidal limits; but, when we find them extending over an area too broad to allow this to be the case, they must have been formed in inland bodies of water, which were periodically laid dry and afterwards refilled.

When these markings have been produced, the return of the water often spreads over them a layer of sand or mud, which seals them up and preserves them.

All these markings are common enough on the surfaces of beds of Sandstones and other rocks of shallow water formation: and on the under surface of the overlying bed a cast appears in relief of the patterns on the bed below.

Summary of Characteristics of Shallow Water Deposits.—The deposits then formed near the shore or in shallow water will be usually coarse and frequently sandy: they will be very changeable in grain and composition, and liable to thin away rapidly in wedge-shaped forms: they will be current- and ripple-drifted, and show signs of erosion and subsequent filling up of the hollows so produced: and their surfaces will be ripple-marked, sun-cracked, pitted with rain-drops, and traversed by the tracks of aquatic animals, and the footprints of wading birds and coast-haunting creatures.

General Character of Deposits of finely divided Matter.—On the other hand we find the very opposite characters to prevail in those accumulations of fine mud, the materials of which can be swept out far from shore, which sink down very slowly, and only reach the bottom after prolonged suspension. Such beds will be uniform in composition over large areas, and will be arranged in layers of regular thickness: traces of current-bedding, contemporaneous erosion, ripple-marks, sun-cracks, rain-drops, and tracks of marine animals will generally be wanting in them.

No better instance of this contrast can be found than in the Oolitic rocks of England. This group consists in the main of three great masses of Clay parted by thick bands of Sandstone and sandy Limestone. The latter are very variable in composition and thickness from place to place, and their lesser subdivisions often thin away altogether, and then after a space set in again. The Clays, on the other hand, stretch in unbroken belts across the island. Even Clay beds however, we have seen, in spite of their greater constancy, must, like all mechanically formed deposits, come to an end somewhere; and accordingly the Clay bands of the Oolites, strikingly persistent as they are, are not absolutely invariable in thickness and composition; they have all one or more spots of maximum thickness, and, as we depart from those, they tail away gradually, and in some cases show us, by becoming sandy and by a decrease in their thickness, that we are approaching the coast line of the old sea in which they were formed.

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* It is stated that ripple-marks have been detected on a muddy bottom at a depth of 188 metres. —(Delesse, Lithologie du Fond des Mers, p. 111).

Deposits, which, though of shallow water origin, are produced by currents too feeble to carry anything but finely divided matter, will be marked by regularity of bedding, but may show ripple-marks and other characteristics of shore formations.

Stratification, and Thickness of Beds.—The subdivision of these regularly bedded deposits into layers, beds, or strata, is owing to pauses in the supply of sediment: whenever these occur, each bed has time to harden a little before the bed next in succession is laid down, and a plane of division between the two is formed. Hence we see, that, if the supply is constant, the thickness of the layers will depend upon the lengths of the intervals between successive pauses. If the supply be continuous, a vast thickness may be accumulated without any bedded structure whatever; this is an extreme case that is but little likely to occur. It happens however not unfrequently, that the intervals of interruption are so short, that only an imperfect degree of bedding can be established: clays deposited under these circumstances often appear quite devoid of stratification, but when weathered or baked, the bedded structure shows itself. On the other hand, where the interruptions to the supply of sediment recur after short intervals, there is scarcely any limit to the excessive thinness to which the beds may be reduced. If we examine the muddy flats that fringe large tidal estuaries, we shall find them covered with a deposit known as Warp, a tough clay which readily splits up into layers no thicker than a sheet of paper. It is formed in this way. At each high tide the flat is flooded by water charged with finely divided mud or sand: during the period of still water before the turn the sediment sinks down and is spread out in a very thin film over the surface; and each film so formed is dried and hardened by evaporation, when the ground is laid dry at low water, before another film is laid upon it by the next advance of the tide.

Parallel between Modern Bedded Deposits and Stratified Rocks.—The examples we have given show that deposits now forming out of sediment carried by running streams into large bodies of still water must necessarily be arranged in layers or beds. We have already seen that a bedded arrangement of an exactly similar character is met with almost universally in one large class of the rocks of the earth's crust. This close resemblance in structure is one good reason for believing that the conclusion arrived at in a particular instance at the beginning of Chapter III., is true generally for the stratified rocks of the earth's crust; and that they have been formed by exactly the same process as is now giving rise to bedded deposits. The other points of resemblance between the two are so close and numerous, that, as one after the other presents itself to our notice, the inference gradually gathers strength, and grows into positive conviction, that an explanation supported by such a body of evidence must be correct.

SECTION II.—MATTER CARRIED IN SOLUTION AND THROWN DOWN BY PRECIPITATION.

We have now to turn our attention to the matter brought down by running water in solution.

One way in which this dissolved matter is extracted and serves to form deposits is by precipitation.

Any solvent, such as water, can dissolve only a certain quantity of the substances soluble in it. If by any means, such as evaporation, the dissolving agent is carried away, the proportion of dissolved matter increases, and the solution is said to become *concentrated*. When this has gone on till the solution holds as much as ever the solvent can dissolve, it is said to be *saturated*. If more of the solvent is removed, some of the dissolved matter is thrown down or *precipitated*. Precipitation is brought about in several ways.

Means by which Precipitation is brought about.—A substance, like Common Salt, soluble in pure water, can be thrown down by evaporation alone. If water is carried away by this means faster than it is supplied, the solution grows more and more concentrated, becomes at length saturated, and then precipitation follows. This is now taking place in the Great Salt Lake of Utah: all around this water there are the traces of old shore lines that show it was once much larger than it is now, it is shrinking because evaporation goes on faster than supply, and consequently it is saturated, and precipitation is forming deposits of Rock Salt on its bed.*

Again there are matters which are not soluble in pure water, but which can be dissolved in water charged with certain substances. In such cases, if the solvent is removed, the matter dissolved by its aid is precipitated. Water, for instance, impregnated with Carbonic Acid can dissolve Carbonate of Lime; but when it both loses Carbonic Acid and becomes itself reduced in bulk by evaporation, the Carbonate of Lime is precipitated. This process goes on to some extent with every spring in Limestone districts, and very largely in the case of those springs which rise from a considerable depth. While shielded from evaporation during their underground course, there is no opportunity for precipitation; but directly the air is gained, or the pressure is in any way lessened, Carbonate of Lime is thrown down. The deposits formed in this way are called Travertin or Calcareous Tufa, and the springs from which they arise Petrifying, or more correctly Encrusting, Springs, because anything placed in them is coated over with Travertin. This is also the origin of those long bodies, known as Stalactites, which hang from the roofs of Limestone caverns; of the lumps of Carbonate of Lime, called Stalagmites, which rise from their floor; and of the sheets of the same substance, which coat their walls. Stalactites may be often seen hanging beneath bridges, the Carbonate of Lime of which they are formed having been extracted by percolating water from the mortar.†

Another cause of precipitation is decrease of temperature. Thus the Geysers of Iceland hold in solution large quantities of Silica: when the water escapes and cools, this is thrown down and forms a rock called Siliceous Sinter. Similar phenomena on a still larger scale are met with in the Yellowstone National Park of the United States.*

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* Sir W. Dilke, "Greater Britain," i. 186.

† Nature, x. 8.

Among the rocks of the earth's crust there are some which have evidently been formed by one or other of these methods of precipitation. It is only in this way that we could obtain great beds of Rock Salt, such for instance as those of Cheshire, Saltzburg, and Wieliczka.

Some Limestones too have all the characters of Travertine, they are porous and still friable and retain traces of plants, shells, and other remains, which have been encrusted by deposition of Carbonate of Lime from solution. There are also calcareous beds with a finely banded structure, which seems to have been given them by the precipitation of very thin layers of Carbonate of Lime one upon the other.

The same structure is met with in siliceous deposits which must have been formed from solution, both on account of their great purity and also because they consist of Silica which has the specific gravity and other characters of the precipitated form of that mineral.

When two or more compound substances are held in solution together, chemical reactions often take place, the compound substances are decomposed and new combinations formed out of their elements, and so when precipitation comes about, the bodies thrown down are altogether different from those originally dissolved. Thus from a saturated solution of Carbonate of Lime and Sulphate of Magnesia, the substances precipitated may be Magnesian Limestone and Gypsum or Sulphate of Lime. Both these rocks enter into the formation of the earth's crust, and it is a very significant fact and very much in favour of their having been formed by some such reaction as that just described that they are constantly found together.† We shall return to this subject in the next chapter.

Conditions necessary for Chemical Precipitation.—We must next inquire under what circumstances chemical precipitation, such as we have described, can take place. The first requisite is a *saturated* solution. Now it is in the highest degree improbable, we might almost say impossible, that the waters of a large open ocean can ever be saturated with the substances brought down into them by solution. The amount carried in this way is, we have seen, very large, and while water and whatever it holds in solution are both of them constantly pouring in, the former alone is removed by evaporation, and the proportion of dissolved matter, if there be no cause which extracts and removes it, is constantly on the increase. But on the other hand the bulk of the water through which this dissolved matter is to be distributed is enormous, and though the degree of concentration must increase as time goes on, a very long time indeed must elapse before anything like saturation can be arrived at; and, long before this time has gone by, some one of those changes in physical geography, which are always going on, will come in to alter the circumstances of the case. But it is altogether different with inland bodies of water of moderate size: in their case there is the same machinery at work tending to produce concentration, and owing to the much smaller mass of water acted upon saturation will be reached in a shorter time. In lakes, which have an outlet, if the discharge is sluggish, the evaporation vigorous, and the incoming streams powerfully charged, a state of saturation *may* ensue and chemical precipitates be formed; but where there is no outlet, it is evident that the solution *must* grow more and more concentrated till this takes place.

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* Nature, vol. vi. pp. 397, 437; Reports of the United States Geol. Survey of the Territories, 1871, p. 100, 1873, pp. 50—57.

† See Sterry Hunt, Silliman's Journ., 2nd ser., xxviii. 170, 365; Geology of Canada, Report up to 1863, p. 575. It is however possible that, in some cases where Dolomite and Gypsum occur together, the first may have been formed by the alteration of the second: See Bischoff's Chemical Geology, i. 420.

For similar reasons all closed bodies of water, even if originally fresh, must become salt in time, because their feeders bring in water plus dissolved matter, and evaporation incessantly removes the first and leaves the second behind to accumulate. The Dead Sea for instance may have been once as fresh as the Lake of Tiberias: we know that in the case of the former water has been for a long time back drawn off by evaporation faster than it is poured in, because there is proof that the lake was once much bigger than it is now, and the result has been a concentration of dissolved matter in it till its present intense saltness was arrived at. From the Lake of Tiberias, on the other hand, water runs out as fast as it runs in, and hence it remains perfectly fresh.

Whenever then we find among the rocks of the earth's crust deposits, like Rock Salt, which can have been produced only by precipitation, we have proof that these deposits were formed not in the open ocean, but in inland bodies of water, and the probability is very strong indeed that these bodies had no outlet.

Chemically formed rocks very generally possess a crystalline structure: and this is one of the exceptions, which the student was told to expect, to the generalisation that bedded rocks are non-crystalline.

SECTION III.—DISSOLVED MATTERS EXTRACTED BY ORGANIC AGENCY.

We have seen how extremely improbable it is that chemical precipitation should go on to any extent in the open sea, and yet there are certain substances, which we know are going down day by day in solution into the ocean, of which scarcely a trace can be found in its waters. Of these Carbonate of Lime furnishes the most striking instance: we need not repeat how largely this substance is dissolved and how steadily it is supplied; it cannot be precipitated, for the Carbonic Acid in sea water is far more than sufficient to keep in solution all the Carbonate of Lime it receives; in spite of this there is in the waters of the open ocean scarcely a trace of it to be found;[*] what then becomes of it? The answer is that it is extracted from the sea water by a host of marine animals to form the stony framework of their bodies and the hard dwellings in which they live. We will now notice some of the most important of these creatures.

Foraminifera.—A very leading part in the process is played by the tiny animals known as Foraminifera. These creatures belong to the Protozoa or lowest sub-kingdom of the animal world, and consist of nothing but a structureless mass of live jelly: some of them have the power of extracting Carbonate of Lime from the water

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[*] This is well brought out by the following analysis of the water of the Clyde above Glasgow, and of that of the Irish Sea at the Bahama Bank lightship, situate in lat. 54° 21′ N., long. 4° 11′ W. (Thorpe, Manual of Inorganic Chemistry, p. 142.) If we call in each case the amount of Chlorine 100, we get—

	River Clyde.	Irish Sea.
Chlorine	100	100
Sulphuric Acid . . .	95	14
Carbonic Acid . . .	377	trace.
Calcium	218	2
Magnesium	57	6·5
Sodium	35	56
Silica	36	trace.

and building up out of it shells, often of the most beautifully regular structure, and in some cases divided into chambers. They have been found in vast numbers over those deep portions of the bed of the Atlantic, which are so remote from land that little mechanically borne sediment finds its way into them, and here the cases of the little creatures fall, after the death of their inhabitants, to the bottom, and form a layer of mealy calcareous mud, to which the name Atlantic or Deep Sea Ooze has been given.*

Now if Chalk be rubbed down with a brush under water and the resulting powder be examined under a microscope, the particles will be found to be almost all of them shells of Foraminifera, some of which are scarcely, if at all, distinguishable from those which go to make up the modern Atlantic Ooze. In other Limestones, harder and more compact than Chalk, similar shells occur in equal abundance. All such rocks, there can be no doubt, whatever be their present character, have been once nothing more than accumulations of Deep Sea Ooze.

A Foraminiferous shell of larger size, known by the name of Nummulite, was at one time extremely abundant, and immense masses of Limestone occur in many parts of the world, which are almost wholly composed of individuals of this genus.

Coral.—Another class of animals, a little higher in the scale than the Foraminifera, which extract Carbonate of Lime from sea water, are the Coral-building Polyps. Some of these, like the common Red Coral of commerce, form only detached branching structures; but others, of which the Brain Coral or Madrepore may be taken as a type, live together in great bodies and build up immense masses of solid rock-like Coral. It is with these latter, which are called Reef-builders, that we are chiefly concerned.

Reef-building Corals require water of a temperature not below 68° F., they can flourish only in water free from mud or sediment, and some of them seem to get on best when they are exposed to the constant dash of the breakers; and they cannot live at a greater depth than about 15 fathoms.†

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* The Depths of the Sea (Professor Wyville Thomson), and the references there to the literature of the subject.

† It has been suggested that temperature is the main cause in fixing the limit below which reef-building Corals cannot live: under certain circumstances then they may be able to live below this limit. Dana however thinks that temperature cannot be the only determining cause (Corals and Coral Islands, p. 118).

The young germs of Coral polyps are free swimming, and we will now consider what would happen, if a colony of them settled down and developed into fixed full-grown individuals, on a shelving shore where the above conditions are satisfied.

As the animals grew and multiplied a layer of Coral would spread over the sea bed; and as the individual polyps increase very rapidly, the reef would grow steadily upwards. In the immediate neighbourhood of the shore the water would be too muddy to suit the Coral builders; here then no Coral would be formed, and the reef would be separated from the land by a channel of water. Wherever a river entered the sea, the mud brought down by it would render the water uninhabitable by the Coral builders for some considerable distance out to sea; hence there would be gaps in the reef facing the mouth of each river. Seawards the Coral building would go on till the depth was reached below which the builders cannot live, and there the reef would end in a steep face. The reef will rise slightly towards the sea, because the builders flourish best and grow fastest on the outside edge where they are exposed to the wash of the breakers.

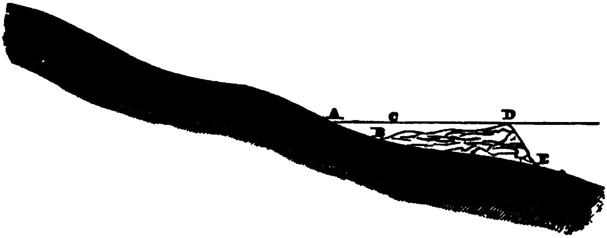

Fig. 15.—Section across a Fringing Reef.

Such a reef as this is called a Fringing reef. A section through it would have somewhat the shape shown in Fig. 15, where AD is the sea-level, ABC the channel between the reef and the shore, and BDE the reef itself.

Next suppose that the country of which Fig. 15 is a section sinks downwards so that the sea level rises gradually to the positions $A_1 D_1$, $A_2 D_2$, $A_3 D_3$, in Fig. 16, and let the rate of sinking be not faster than the rate at which the Coral animals can build up their reef. Then the Coral will go on growing upwards and be added in tier above tier, such as $B\,B_1\;D_1\,D$, $B_1\,B_2\;D_2\,D_1$, $B_2\,B_3\;D_3\,D_2$. No growth can take place on the seaward side of the reef, because the water is too deep; and a space between it and the land will be kept free from Coral, partly by the muddiness of the water, and partly by the scour of the current, which is produced by the washing of waves over the top of the reef and the escape of the water through its openings. Thus will be produced a mighty wall of Coral rock, separated from the land by a deep and broad channel, and bounded on the seaward side by a face almost vertical and of enormous height. Such a reef is called a Barrier reef. There is such a reef fronting the north-east coast of Australia, 1,250 miles long, from 10 to 90 miles broad, and with a sea front exceeding in some places 1,800 feet in height: the channel between it and the sea is from 20 to 70 miles wide. A better idea of its size than mere figures will give, will be conveyed by the consideration, that such a reef would reach from the Land's End along the shores of the British Isles up to and beyond Iceland.

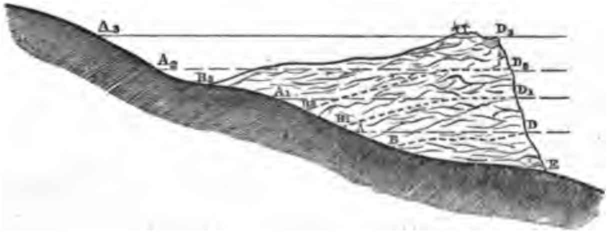

Fig. 16.—Section across a Barrier Reef.

Barrier reefs are breached every now and then by openings, and *these always face valleys on the land fronting the reef.* They are in fact the gaps which were originally established in the earlier form of the Fringing reef, and have been kept open by the scour of the tide and currents.

One more form of Coral reef, by far the most singular of all, remains to be described.

Imagine an island surrounded by a Fringing reef to be slowly submerged, so that the Fringing reef becomes converted into a Barrier reef. As the sinking goes on, the amount of land above the water grows less and less, while the encircling girdle of Coral keeps growing upwards. At length the last peak disappears below the sea level, and there remains only a ring of Coral enclosing a lagoon.

Some of the old breaches in the original reef occasionally remain open and yield an entrance from the open sea into the lagoon. Such reefs are called Atolls or Coral Islands: they are plentiful in the Pacific and Indian Oceans, and vary in size from less than a mile up to 80 miles in their longest diameter.

Fig. 17 is a diagrammatic section and Fig. 18 a view of an atoll.

In the first the black part represents the original island, $A_1 D_1$, $A_2 D_2$, $A_3 D_3$ the levels of the sea at different times during the submergence, and the successive additions of Coral rock are denoted in the same way as in Fig. 16.

The shape of the encircling Coral belt depends of course on that of the land on which it is based, and hence atolls are annular, triangular, many-sided, and even of more complicated forms. The openings into the lagoon are often closed, and the lagoon itself filled up by Coral growth or accumulations of fragments, powder, or mud worn off the reef and driven inwards by the breakers.

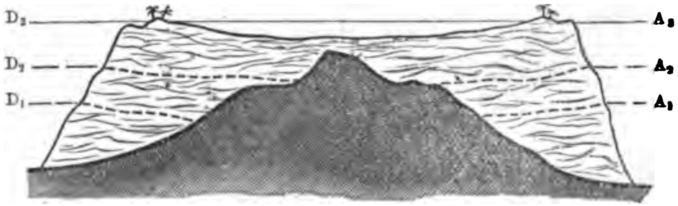

Fig. 17.—Section across an Atoll.

The sketches in Figs. 15—17 are mere diagrams, and do not show either the details or the true proportions of a barrier reef or atoll: these will be learned from Fig. 19, which is a section more nearly to scale across the rim of a reef.

a b is a platform nearly at low-tide level, called by Dana the shore platform, almost flat, but rising slightly towards the seaward edge. Towards the open ocean the water for from 100 to 500 yards (*a* to *m*) deepens slowly, and there is then an abrupt descent at angles varying from 40° up to absolute verticality. At *b* there is a sharp rise of from six to eight feet, which brings us on the portion of the reef (*b c*) which is permanently above water; *c d* is a gently sloping beach bordering the lagoon or inner channel; and from *d* the surface passes down, gently at first and then more

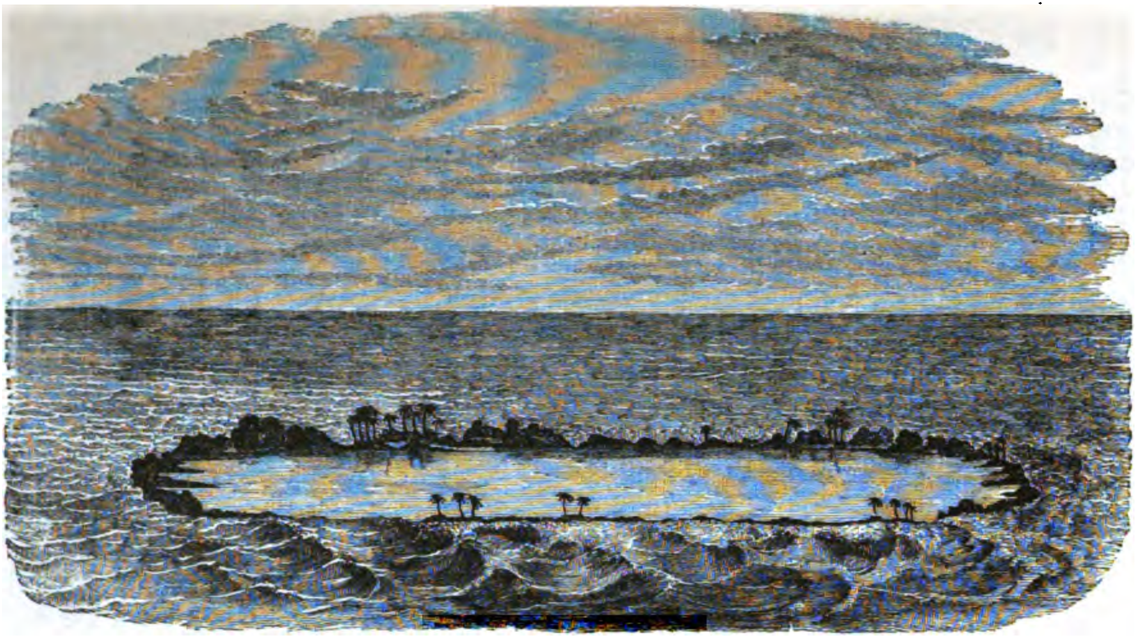

Fig. 18.—VIEW OF AN ATOLL.

steeply, beneath the waters of the latter. Over *a m* there are various Coral growths going on, which will be more specially noticed shortly.

Coral reefs are composed of pure Carbonate of Lime, and therefore the Coral builders provide the materials for the formation of Limestone in plentiful abundance. In some cases these masses are preserved and form rocks in their original reef-like form. If a shelving beach, on which fringing reefs are growing, be slowly upheaved, the Coral raised out of the water will die; but on the seaward side of the reef a fresh belt of water will be rendered shallow enough for the Coral builders to live in it, and the reef will continue to grow outwards. This has taken place on the peninsula of Florida, which shows ranks of Coral reef, one within the other, raised successively by gradual upheaval.

Again curious structures are often produced by the growth of detached masses of Coral in regions of shallow water outside a reef or in the lagoon or channel within. Such are shown in Fig. 19, rising in slender pillars almost up to the surface of the water, when they spread out into large tabular masses. Sometimes the heads join together and so enclose large cavernous recesses. The cavities between these branching masses gradually get filled in with debris worn by the breakers off the reef, and the whole becomes cemented by the percolation and evaporation of water holding Carbonate of Lime in solution into an extremely hard and solid rock.[*]

We find occasionally among the older rocks of the earth's crust masses of Limestone, which are more or less made up of Coraf reefs scarcely altered at all in structure and form from the condition in which they grew; and the examples just given enable us to realise how they were formed. Such Coral beds enclose sometimes the remains of shells, fish, and other marine animals that lived in the water where they grew.

But Coral reefs are incessantly exposed to the severest form of marine denudation; the beating of the breakers on their seaward face tears off and hurls on to the top of the reef huge masses of Coral, and some of these are there rolled about and ground down into calcareous powder. Some of this comminuted matter is thrown on shore, and there cemented by water holding Carbonate of Lime in solution into a hard rock. Here is an instance. "The beach of this island (Heron Island) was steep, about 20 feet high at low water, and composed partly of sand and partly of stone. The sand was very coarse, composed wholly of large grains and small angular pieces of broken and comminuted shells and corals, with some large worn fragments of both intermixed. The stone was of precisely the same material, but very hard; dark brown externally, but still white inside. It sometimes required two or three sharp blows with a hammer to break off even a corner of it. Its surface was everywhere rough, honeycombed, and uneven; the beds were from one to two feet in thickness, with occasionally in the fine-grained parts a tendency to split into flags or slabs. It was perfectly jointed by rather zigzag joints crossing each other at right angles, and splitting the rock into quadrangular blocks of from one to two feet in the side. As far as external appearance and character went, it might have been taken for any old roughly stratified rock."*

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[*] Dana, Corals and Coral Islands, pp. 141—144.

These formations of beach Limestone often possess the structure which will shortly be described as Oolitic. Very closely grained, compact Limestones are also formed by the cementing together of the more finely comminuted Coral debris.

The wind aids the waves in the work of supplying

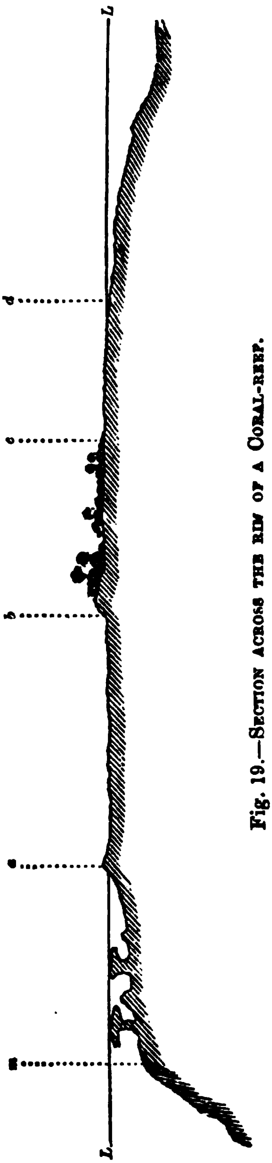

Fig. 19.—Section across the rim of a Coral-reef.
L L, level of low tide.

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* Jukes, Eastern Archipelago, vol. i. p. 7.

materials for beach formations, carrying the finer debris on to the permanently dry part of the reef, where it becomes cemented into rock.

But a very large part of the debris of Coral reefs is swept out to sea, and, mixed with sediment carried down from the land, gives rise to deposits of sandy or earthy Limestone. There is stuff enough in the Barrier reef of Australia to cover the whole bed of the Atlantic to a depth of two feet or so, so that the degradation of this reef alone would furnish the materials for an enormous bed of Limestone.*

Other Limestone-secreting Animals.—There are other limestone-secreting animals besides those mentioned, whose hard parts serve to make up beds of that rock. Thus some Limestones are composed of little else but the joints and columns of Sea-lilies or Encrinites; when polished these form a coarse marble and are largely used for mantelpieces: in other cases Oyster banks or accumulations of the shells of other mollusca are compacted into Limestone.

Certain seaweeds too, such as the Corallines, secrete Carbonate of Lime about their tissues, and these grow so abundantly on some coasts, that, when broken up and accumulated along the shore, they make thick calcareous deposits.

Origin of pure Limestones and Inference from their presence.—One most important generalisation can be drawn from the facts we have been just considering. Great masses of marine limestone are formed by the intermediate agency of animals, and, as far as we know, *they can be formed in no other way.* If therefore among the rocks of the earth's crust we find such masses of limestone, *they are in themselves a proof of the existence of animal life on the earth at the time of their formation, even though actual remains of animals may no longer be recognisable in them.*

Place of Limestone in the Sea Bed.—As a rule too limestone-secreting animals can flourish only in pure water free from sediment: *the formation of organic limestone on a large scale can therefore go on only at spots so far remote from land that no mechanically carried sediment finds its way to them.* Just in the same way therefore as sandy and pebbly deposits point to shallow water and the neighbourhood of land, and finely laminated muddy beds to a portion of the sea-bottom rather further from the shore, so great bodies of pure marine limestone show, that the spot where they occur was, at the time of their formation, far out at sea and frequently that it was in deep water.

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* Our knowledge of the method of the growth of Coral Reefs is due to Darwin, and the reader should fill in the above sketch by a careful study of his writings on the subject, originally published in the Geology of the Voyage of the *Beagle*, and lately reprinted in a separate volume.

Animals and Plants secreting Silica.—Silica is another substance largely carried away in solution and recovered by organic agency.

Diatoms and some creatures allied to Foraminifera (Polycystinæ) form in this way siliceous shells, and the spiculæ and framework of many sponges are composed of the same material. The cases and hard parts of such creatures accumulate on the sea-bottom after the death of their owners, and furnish materials for siliceous deposits of organic origin. In some cases a sea-bed seems to have been peopled almost exclusively by tiny silica-coated creatures, and in these cases their shells form beds of siliceous rock. Tripoli or Polishing Slate is the best known instance.

In other cases the animals with siliceous coats live alongside calcareous Foraminifera, forming however only a minority of the inhabitants of the sea-bottom. The rocks, which have been produced under these circumstances, do not in many cases contain, as might be expected, Silica disseminated throughout their whole bulk; as a rule, Silica is present to a comparatively small extent in the body of the rock, and occurs chiefly in lumps and nodules. Flints in Chalk will occur to every one as an instance of this, and similar siliceous nodules are found almost universally in organic Limestones. We can only say in this case, that the Silica, which must have once pervaded the whole rock, has been separated out and gathered together into nodules; how this was done we cannot at present explain. The name Concretionary Action is given to the process, which will be touched on again by-and-by.

Red Clay of the Atlantic.—There are some deposits, apparently differing in their origin from any yet described, which the soundings of the *Challenger* Expedition have shown are now in process of formation over the very deepest parts of the bed of the ocean. The general results of these explorations of the sea-bottom are, as far as they have been at present made public, as follows.

The Atlantic or Globigerina Ooze covers, as has been already mentioned, very extensive tracts; down to a depth of two thousand fathoms the shells retain nearly all their Carbonate of Lime, and the deposit is essentially calcareous; beyond that depth this calcareous slime gradually becomes more and more clayey, and passes into a deposit to which the explorers have given the name of Grey Ooze. In the Grey Ooze the shells of the Foraminifera can still be detected, but they have lost much of their sharpness of outline, assume a kind of rotten look and a brownish colour, and become mixed with a fine amorphous red-brown powder. As the depth increases the proportion of this powder grows larger and larger, the traces of calcareous matter decrease and at last disappear altogether, and the deposit assumes the form of a red clay in the finest possible state of subdivision. The red clay is found to be a silicate of alumina and iron.

The great value of this discovery from a geological point of view is this. We should be inclined at first sight to think, that this red mud is, like the clayey deposits we have hitherto been dealing with, of mechanical origin; and that it is found only at great depths and far from land, because, being very fine, it took a very long time to settle down; that it is in fact the impalpable residue of river-borne sediment which remained in suspension after the coarser part had sunk to the bottom. But a very little consideration will show us that such an explanation will not fit in with the facts of the case. If this were the origin of the red clay, we ought to be able to trace a connection between it and the land by whose wear and tear the materials for it were furnished; we ought to be able to follow it, growing gradually coarser and coarser, up to the rivers that brought these materials into the ocean. But no such connection exists; the red mud occurs only over the deepest parts of the sea-bed, and between it and the land there lie broad tracts covered with Globigerina Ooze, and absolutely free from any trace of mechanical deposit whatever. Its isolation therefore proves that it did not come from land, and it must have arisen in some way or other on the areas to which it is confined. How it was formed is still far from settled; the passage from Globigerina Ooze through Grey Ooze into the Red Clay is so insensible, that it seems highly likely that the two last have been formed out of the first by the gradual removal of its carbonate of lime, and Professor Wyville Thomson suggests this may have been brought about in the following manner. He believes that the Globigerina live on the surface, and that when they die their shells sink slowly to the bottom; as they pass downwards the carbonate of lime is dissolved out by the aid of the carbonic acid contained in the sea-water; the greater the depth through which they sink, the longer will they be exposed to this action, and the more complete will be the extraction of the carbonate of lime; if the depth be great enough, the carbonate of lime will be entirely taken away, and there will remain only the earthy insoluble portion of the shell, and this he thinks is the material of which the red clay is composed. Whether his explanation be correct or not, the red clay is there, it is not a product of denudation, and it is in some way or other connected with the organic deposits of the Globigerina Ooze, and we have learned that clayey rocks may be formed by organic agency in the most remote and the deepest parts of the ocean. Professor Thomson points out the possibility of some fine homogeneous clayey rocks of the earth's crust having been formed by methods similar to that which is now producing the red clay.*

SECTION IV.—TERRESTRIAL DEPOSITS.

We have now dealt with that portion of the waste of denudation, by far the larger part, which is carried down into bodies of still water, and have described the different ways in which it becomes arranged in bedded deposits.

A certain portion however of denuded matters is a long time in making its journey, and often tarries on its way, forming accumulations on dry land distinguished as Terrestrial.

The Terrestrial deposits of the present day are far from being insignificant; and now that we have found so many rocks that bear a close resemblance to denuded matters which have been arranged under water, the question naturally suggests itself, whether there are any rocks approaching in the same way the accumulations of the products of denudation on dry land.

We cannot reasonably expect to find among the rocks of the earth's crust many which correspond to the Terrestrial deposits now going on. These accumulations are so liable to be broken up and carried away by a continuance of the denuding processes which gave rise to them, that it is only as it were by some happy accident that they survive at all the wear and tear which the surface is always undergoing, and, when they do manage to escape total destruction, as a rule only fragments of them are preserved. But we can imagine, that, if ground is let down very gently beneath water, the loose matters lying on its surface may become submerged without being destroyed, may be covered up by subaqueous deposits, and may be handed down as the relics of a land surface that has long passed away.

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* See Nature, xi. 95, 116; xii. 174. Also Professor Huxley, "On some of the Results of the Expedition of H.M.S. *Challenger*," Contemporary Review, March, 1875, in which paper the reader will find an admirable summary of what is known on the subject of organic deposits, and references to original memoirs.

Soil and Rain-wash.—Under the present head come the deposits of rain-wash described in the last chapter, and the surface soil formed partly by the breaking up of the underlying rock and partly by the decomposition of vegetable matter.

The remains of old soils, still penetrated by the roots of plants that grew in them, and with the stools, and occasionally the trunks, of trees in the position in which they grew, are now and then found among solid rocks. One of the best known cases is the "Dirt Bed" of the Island of Portland and the adjoining coast, a section of which is given in Fig. 20. The lowest beds (1) are Limestones proved by their fossils to have been formed beneath the sea; on these there rests a thin band (2) of dark earth, full of angular fragments of the underlying Limestone and containing the stools of large plants allied to the modern Cycas, with here and there prostrate trunks of trees: above this come other Limestones (3), containing fossils which show them to be of estuarine origin. The surface is formed by a "brashy" or stony soil (4), composed partly of dark vegetable matter and partly of fragments of the rock (3). Now even if the plants in the band (2) did not clearly bespeak its origin, we could not fail to be struck by the close resemblance which it bears to the present surface soil (4). There is no rounded or foreign stone in it, all the fragments are of the rock immediately beneath, it is as true a "brash" as the loose matter at the top of the section; and the dark earth, in which the stones are embedded, is unmistakably vegetable soil. The roots of the plants, though their evidence is scarcely needed, furnish additional proof that we have here an old land surface; that before the deposition of the beds (3) the lower Limestones had been raised into the air and supported vegetable growth; that partly by the decay of plants and partly by the atmospheric breaking up of the rock the band (2) was formed; that the whole was then sunk beneath water in which the rocks (3) accumulated, and

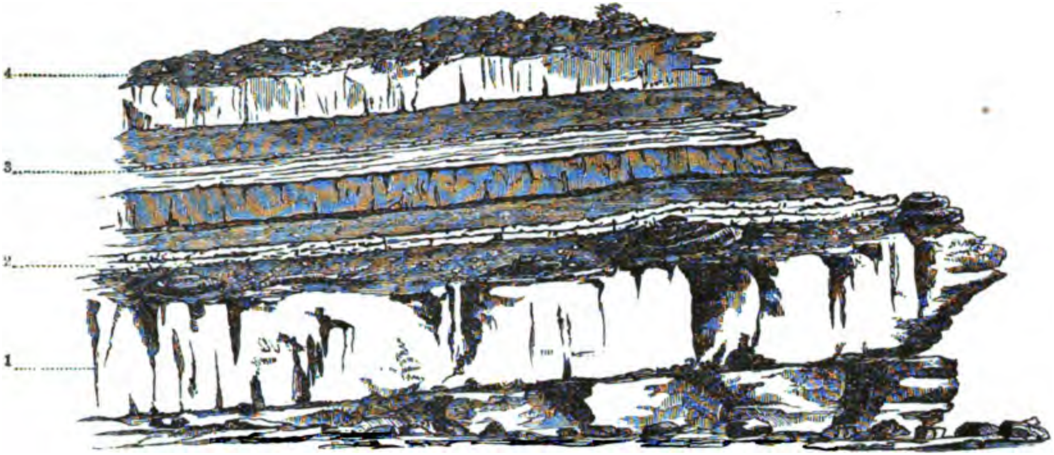

Fig. 20.—Section of the Dirt Bed of the Dorsetshire Coast.

1. Marine Limestone. 2. "Dirt Bed," old brashy soil with stools and trunks of trees. 3. Estuarine Beds. 4. Modern brashy soil

that the submergence was so gentle that the loose surface covering was not swept away. The lower portion of the beds (3) will be observed to be bent up over one of the stools, which projects above the surface of the "Dirt Bed." Occasionally two dirt beds are seen in the section, showing that the process happened twice over.

We shall notice still more striking instances of the preservation of old vegetable soils, when we come to consider the formation of Coal.

In some cases old soils have been sealed up and preserved by sheets of lava that have flowed over them. Thus in Madeira Sir C. Lyell has described red partings of laterite or red ochreous clay between sheets of basalt. "These red bands vary in thickness from a few inches to two or three feet, and consist sometimes of layers of tuff, sometimes of ancient soils derived from decomposed lava, both of them burnt to a brick-red colour, and altered by the contact of melted matter which has flowed over them."* Similar intercalations of red earth, which also probably represent old land surfaces, occur among the basalts of the north-east of Ireland and of the western islands of Scotland. They consist of bands of clay and earth, usually only a few inches in thickness, of a bright red colour, and appear to be beds of soil formed by the weathering of the surface of one lava stream, which were afterwards burnt to their present colour when they were overwhelmed by the next sheet of lava. Accumulations of vegetable matter, sometimes converted into charcoal and sometimes forming Lignite or Coal, are also met with in similar positions, and these may occasionally be observed to rest on a soil, in which the roots of the plants can still be detected.†

Screes.—At the foot of cliffs, both inland and on the sea coast, and on steep rocky hillsides, fragments of disintegrated rock accumulate in great piles of angular blocks, which are known as *Screes*. These are sometimes rolled by the waves and spread out in sheets of coarse shingly Conglomerate; sometimes they are covered up pretty much as they lie and give rise to breccias.

A capital instance of a deposit which has arisen in this way is furnished by the Dolomitic Conglomerate of the south-west of England, the nature of which is shown on the section in Fig. 21.

The country crossed by the section is a plain of red Clays and Sandstones (*c*) in which there stand up every here and there isolated hills of hard Limestone (*a*). Every one of these hills is fringed by a bank of coarse Conglomerate and Breccia (*b*), made up of rounded boulders, pebbles, and angular blocks of the Limestone (*a*); in each case the Conglomerate is thickest in the immediate neighbourhood of the Limestone hill which it surrounds, grows thinner as we recede from that hill, and at length wholly disappears.

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* Elements of Geology, 6th ed., p 639.

† Judd, Quart. Journ. Geol. Soc. of London, xxx. 227.

The Conglomerates and Clays are interbedded in such a way that it is evident that the formation of the two must have gone on together, and the steps of the process must have been as follows. The country was at one time covered by a broad sheet of water, in the middle of which bosses of the Limestone (*a*) stood up as islands. Into this water rivers carried down red mud and sand, which furnished the materials for the beds (*c*). On the exposed surfaces of the islands subaërial waste gave rise to an accumulation of Screes, at the same time that the red beds were being regularly laid down in the surrounding water. After a time the land sank, and the water encroached over a portion of what had previously been dry land; the submerged part of the Screes became thus covered up by layers of red beds, and appeared as a wedge-shaped mass of Conglomerate interstratified with the latter. By a repetition of this process the successive alternations of red Clay and Conglomerate were produced. Round the margin of the

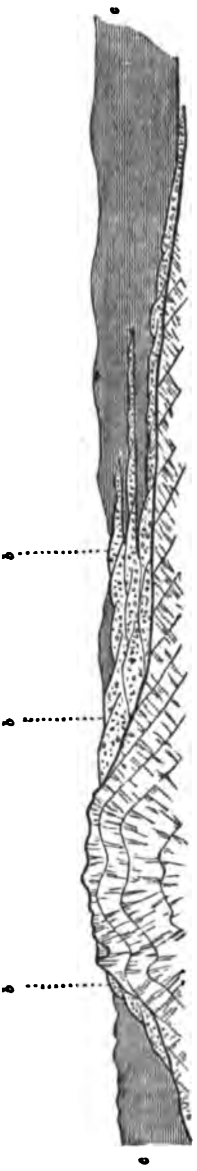

Fig. 21.—Section showing the Position of the Dolomitic Conglomerate of the South-west of England.

a. Carboniferous Limestone. *b.* Dolomitic Conglomerate. *c.* Red Clays.

islands it would also happen that the waves would play upon the accumulations of debris, round its fragments into pebbles, and spread them out in layers of shingly Conglomerate among the more quietly deposited strata of Clay. The subaërial character of these Breccias is borne out by the fact that they contain the bones of two genera of terrestrial reptiles.*

There are some curious brecciated deposits among the Permian rocks of Cumberland and Westmoreland, known by the name of "Brockrams" and "Crab Rock," some of which seem to be old Screes.†

Blown Sand.—Another very common form of terrestrial accumulations is that of Blown Sand. In many cases we find the seashore fringed by a belt, often of considerable breadth, of hillocks or Dunes of Sand, which has been dried by the wind and blown inland from the beach. Similar piling up of sand goes on in large deserts and other sandy tracts of the earth's surface. These sandy accumulations often show, when cut into, rude bedding, and the action of the wind produces in them structures exactly analogous to the current-bedding and ripple-drift of subaqueous sandstones. In some cases the sand is mixed with broken shells, and water, percolating through the mass, dissolves out their Carbonate of Lime and redeposits it as a cement, so that a hard calcareous Sandstone is produced. Should any of these accumulations of Blown Sand be preserved in the manner just described, it would be almost impossible to distinguish them from Sandstones formed beneath water, unless they happened to contain land shells or land plants in the position in which they grew. It is therefore possible that some of the sandstones of the earth's crust may have been originally Blown Sand.

Rocks of Vegetable Origin.—Perhaps the most important of terrestrial deposits are those of vegetable origin. There are plants, such as the peat mosses, which in cold temperate climates form in swampy situations and hollows broad and thick sheets of vegetable matter known as peat mosses. When the lower parts die, the upper surface lives on and grows upwards, and the sheet of vegetable matter continues to increase in thickness.‡ The peat bogs of our own islands and the Great Dismal Swamp of Virginia are well-known instances of these vegetable accumulations.* We must now explain how such layers of dead plants have given rise to rocks.

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* De la Beche, Memoirs of the Geol. Survey of Great Britain, i. 240; Geological Observer, p. 550; Etheridge, Quart. Journ. Geol. Soc., xxvi. 174; Huxley, Ibid., 42.

† Quart. Journ. Geol. Soc., xx. 149, 152. For another case, see Judd, Quart. Journ. Geol. Soc., xxx. 281, Fig. 9, and 286.

‡ J. Geikie, Transacts. Royal Soc. of Edinburgh, xxiv. 363.

Coal.—We can readily imagine an accumulation of dead land plants, like a peat bog, being let down gently beneath water, covered up by deposits of sediment, and preserved in the middle of a mass of bedded sand and mud. This is now admitted to have been the origin of beds of Coal, the conclusion having been come to by the following line of reasoning.

As has been already explained, it has long been allowed on all hands that Coal is of vegetable origin; but at one time great difference of opinion existed as to how the vegetable matter out of which it is formed was brought together. Some geologists would have it that Coal was an accumulation of drift plants, just as Sandstones and Shales are accumulations of drifted sand and mud. There are several very strong objections to this view. Many Coal seams extend with a fairly regular thickness over tracts hundreds of square miles in area, and it is not easy to see how such a light matter as dead wood could be spread out in even and regular layers of such great extent. Again the better kinds of Coal are nearly pure vegetable matter, and contain only a very small percentage of sandy and clayey admixtures. Such purity of composition is hardly explicable on the Drift theory, for the water that carried down the dead plants would bring also sediment, the two would be inevitably mixed up together, and the result would be a sort of Coal certainly, but a Coal far more earthy, and producing when burnt a far larger quantity of ash, than the majority of Coals in use. It is found too in some cases that the small quantity of impurity which Coal does contain agrees in amount and composition with the earthy portion of living plants. So that the whole of Coal, both its carbonaceous part and its ash, may have come from a vegetable source.

Some other explanation had therefore to be sought for, and the first step in the right direction was made by Sir W. Logan. He pointed out that every bed of Coal rests on a peculiar clay, to which the name Underclay, Seat-earth, or Warrant is applied. These underclays vary very much in mineral composition and other respects, but they all agree in two points: they are unstratified and break up into irregular lumpy fragments, and they always contain a peculiar vegetable fossil known as Stigmaria. These Stigmaria are long, branching, cylindrical bodies, dotted over with regularly arranged pits or scars, from which long ribbon-shaped filaments run out in all directions, till the Clay is sometimes one thickly-matted mass of them. The Stigmaria lie parallel to the bedding, and their position and the root-like processes that spring from them suggest naturally the idea that they are roots. That this is really their character was first proved by Mr. Binney. He discovered in a railway cutting near Manchester the trunk of a tree, very commonly found fossil in the measures associated with Coal and known by the name of Sigillaria, standing erect as it grew and still connected with its roots. These roots were Stigmaria, and the bed into which they struck down was an underclay. Many similar cases have since been observed. The mystery was now fully solved: the Under-clays are old terrestrial soils, and the trees and plants that grew upon them, as they died and fell to the ground, formed a layer of nearly pure vegetable matter: after a time the surface was lowered beneath water, but so gently that the soft pulpy mass was not disturbed, sand and clay were laid down on the top, and the band of dead plants was thus sealed up, preserved from decay, and converted by pressure and chemical changes into a seam of Coal.*

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* Sir C. Lyell, Travels in North America, i. chap. vii.

Fig. 22 shows a bed of Coal and its underclay: the Coal has been removed in the front part of the diagram so as to lay bare the underclay and show the *Stigmaria.*

Fig. 23 will give an idea of one of the erect trunks just mentioned. The beds in the upper part of the diagram are Shales and Sandstones, which have accumulated round the trunk; beneath these is a thin bed of Coal, and that rests on an underclay into which the roots strike down.

Subaqueous Coal.†—That most of our Coal seams have had their origin in the manner described is beyond question, but we do occasionally meet with Coal which has been formed under water out of masses of drift timber and plants carried down by rivers and buried among mechanical

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* Steinhauer, American Phil. Transactions, new series, vol. i.; Logan, Transactions Geol. Soc. of London, 1842; Binney, Phil. Mag., 1844, 1845, 1847; Quart. Journ. Geol. Soc., ii. 390, vi. 17; Transactions of Manchester Geol. Soc. i. 178; Bowman, Ibid. i. 112; Brown, Quart. Journ. Geol. Soc., ii. 393; Geology of the South Staffordshire Coalfield (Mems. of the Geol. Survey of England and Wales), 2nd ed. p. 216, and the references in the note to p. 78.

† These rocks ought by good rights to be placed under Section I; it is however more convenient to consider them here.

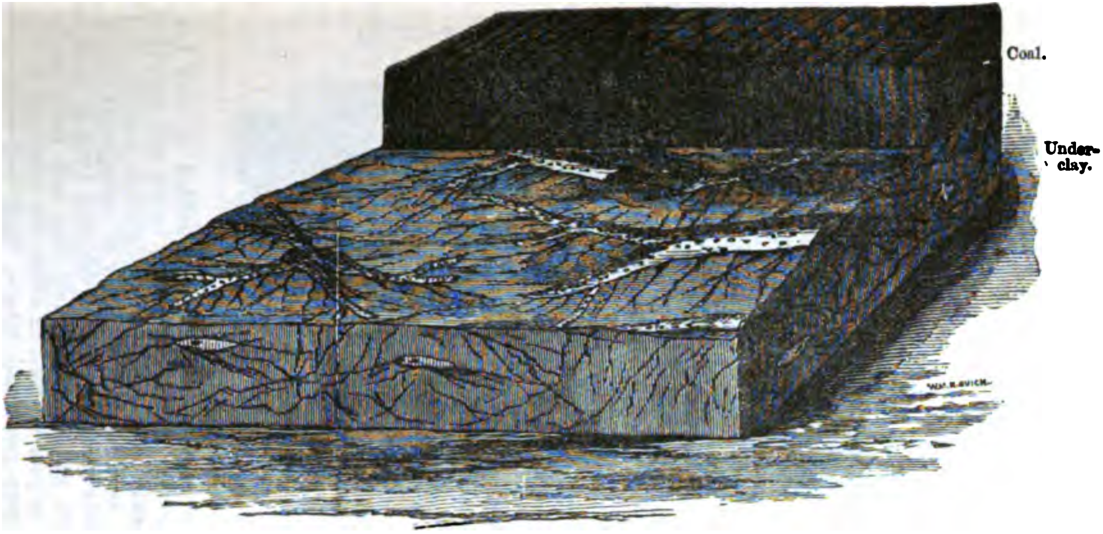

Fig. 22.—Coal resting on an Underclay with Stigmaria.

deposits. Such Coal occurs however rather in lenticular patches than regular beds, and is apt to be impure from a mixture of earthy sediment.

In the middle of sandstone beds too little nests of Coal often occur, which must have been formed in this way;

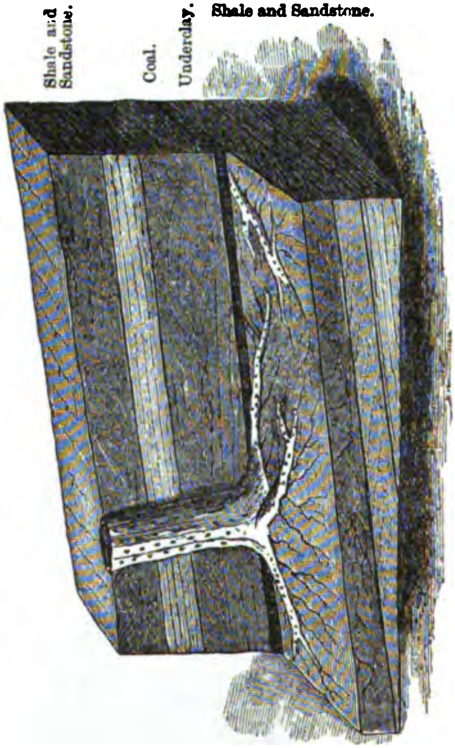
Shale and Sandstone.
Coal.
Underclay.
Shale and Sandstone.

Fig. 23.—Erect Sigillaria with Stigmaria roots.

and the bark of fossil trees embedded in rock has frequently been converted into very bright and pure Coal.

Cannel Coal.—One very important variety of Coal, known as Cannel, is probably of subaqueous origin. It invariably occurs in patches thinning away to nothing on all sides, and it seems likely that each patch marks the site of a pool or lake, in which the vegetable matter lay till it was macerated into a black carbonaceous pulp.

Many facts lend support to this view. The remains of fish are of constant occurrence in Cannel Coal, and they could not have got there unless the bed was formed beneath water. Beds of Cannel also pass by a gradual increase of earthy admixture into well stratified black carbonaceous shale; and we can readily imagine how this would come about, if the stream carried at the same time mud and plants into a lake. The heavier sediment, stained by some vegetable matter, would sink down first, the lighter wood would float to greater distances, and thus near the mouth of the river the deposit would be mainly black mud, further on in the pool the proportion of vegetable matter would increase, and at last, when all the earthy sediment had been strained out, there would be accumulations consisting almost entirely of drifted plants, which continued soaking would reduce to just such a pulp, as, when compacted, would furnish a Cannel Coal.

Partings in Coal Seams.—Thick seams of coal are very frequently made up of a number of different beds separated by layers or "partings" of shale or sandstone, and these partings are very variable in thickness; we frequently find that a parting, which has been a mere fraction of an inch in thickness over a large area, swells out in a certain direction till it becomes many feet thick. The Thick Coal of South Staffordshire for instance is in the centre of the field a mass of coal 30 feet in thickness, and is practically a single seam; even under this form, however, it is readily seen to be made up of a number of beds, parted from one another by planes of stratification, and differing in character and quality; as we trace the seam northwards, partings come in between the beds and thicken to the north, and in a space of five miles the single seam of 30 feet has become split up into ten coals, which, with the measures between them, make up a thickness of 500 feet.*

We can readily understand how partings were formed. When a certain thickness of vegetable matter had accumulated, it was lowered beneath water, and mud or sand deposited on the top; but the submergence lasted only for a very short time—only long enough to allow of a very thin layer being laid down; then the whole was raised again and vegetable growth and formation of Coal began afresh.

The thickening of a parting must have been brought about somewhat in the way shown in Fig. 24. The lower bed of Coal was first formed, and then submerged; but the sinking gradually increased in amount from the left to the right, so that the Coal was brought into the position *a b;* then deposition of sediment levelled over the inequalities produced by unequal subsidence up to the line *c d;* then the whole was raised, and on the level flow *c d* another seam of Coal grew.

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* Geology of the South Staffordshire Coal Field (Mem. of the Geological Survey of England and Wales), p. 25.

There are also irregularities in beds of Coal which admit of a somewhat different explanation. Let *a b*, *c d*, in Fig. 25, be two level tracts, over which coal-growth is going on, separated by a rising boss of land on which little or no vegetation flourishes. Water running down the flanks of the rising ground will carry sediment on to the levels on either side, but when it reaches the flat ground the water will come to rest and the sediment will be quickly thrown down. Hence banks of sand or mud will form round the boss at the same time that Coal is growing further away from it; but these banks will thin away rapidly as we recede from the boss, and at a little distance from it the growth of Coal will go on without any admixture of sediment with the vegetable matter. The formation of the seam may be supposed to begin with the growth of the layer *e*, which thins away and ends off against the boss; then the bank of sand *f* and the layer of Coal *g* may be formed at the same time; then there may be an addition of Coal *h* on the top of *g*, which extends itself over the top of *f* up to the boss; on the top of this another sandbank may be deposited on the right, and more Coal grow on the left. A repetition of this process will give us a thick bed of Coal free from partings on the left, which, as we go to the right, is split up by partings till nearly all the Coal has disappeared. The same result will be produced over the flat *c d;* and when the seam comes to be worked, it will be found clean and good at *a* and *d*, but as we approach the middle of the diagram will appear to change into a mass of Shale or Sandstone containing a number of thin layers of Coal. Cases of this sort are of very frequent occurrence.

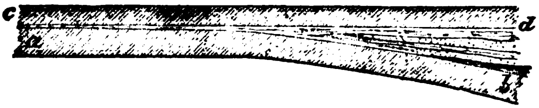

Fig. 24.—Diagram to explain the thickening of a Parting in a Seam of Coal.

The terrestrial deposits produced by the action of ice, which are very extensive and of great importance, will be treated of in the next section.

SECTION V.—DEPOSITS OF ICE-FORMED DETRITUS.

Much of the waste produced by the action of ice is carried to its resting-place in the same way as the products of other denuding forces; in some cases, however, ice itself acts as a carrier, and the accumulations thus produced differ in many important points from any we have yet considered. But whether borne away by moving ice or running water, the deposits due to ice-action have so marked and distinctive a stamp, that they may very properly be placed in a section by themselves.

Distinctive Characters of Ice-borne Detritus.—We will first point out what the characters are which are peculiar to ice-borne detritus, and enable us to distinguish it from that carried by rivers.

The latter necessarily undergoes wear and tear and becomes more or less rounded: also running water cannot transport to any great distance blocks of large size. By means of moving ice on the other hand blocks of enormous size may be carried without any rounding at all; by land-ice they may be borne away from a mountain-top across valley and hill, and dropped far away from their parent home almost as sharp and angular as when first broken off, and icebergs can float them with as little wear to still greater distances.

Also the sediment carried by running water will, when it comes to rest, be arranged to a certain degree according to the size and weight of the fragments: the heavier and coarser will fall down first, and the lighter and finer will remain longer in suspension, and settle down further off from the source of supply. Such deposits will also be arranged in beds or layers. But in the case of the stuff shot over the end of a glacier, or dropped from a floating iceberg, or churned

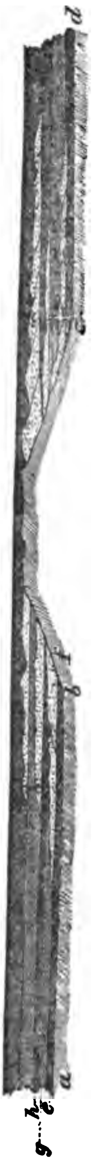

Fig. 25.—Diagram to explain the gradual replacement of Coal by Sandstone and Shale.

up beneath a sheet of continental ice, there will be no sorting of this sort: big blocks and fine earth will be heaped pell-mell together without regard to size or weight, and the former, instead of sinking on to their broad sides, may be packed on their smaller ends or edges: there will also be little or nothing of bedded arrangement in the deposits formed by land ice.

But the most easily recognised and unmistakable sign which ice leaves of its handiwork has yet to be pointed out. The stones frozen into the under surface of a mass of moving ice, and the stones over which it passes, mutually smooth and cut into one another. Two large stones by rubbing against one another become worn flat, and often polished as thoroughly as if they had passed through a lapidary's hands: the harder and sharper stones act as cutting tools, and grind grooves in whatever they pass over, ranging in size from ruts big enough for a cart-wheel to run in, down to scratches as fine as the lines of a steel engraving. Markings like these have a peculiar stamp of their own, and no one who has once seen such can ever fail to recognise them again. As far as we know the like are made by no agent but moving ice.

Whenever then we find a deposit containing far-travelled blocks of large size and but little rounded, the materials of which are heaped together in a confused way without regard to size or weight; which shows no bedded structure or only rude traces of bedding; and which contains polished and scratched stones, or stones that retain traces of former polishing and scratching; we may safely conclude that ice has been concerned in the formation of that deposit, even though the country in which it occurs cannot now nourish large masses of ice.

Forms of Glacial Deposits.—Deposits formed by the action of ice are called Glacial, and may be considered under the following heads: Till; Moraines; Glacial Mud; subaqueous accumulations containing the droppings of Icebergs or an Ice Foot, which may be distinguished as Boulder Clays *; Erratics; and deposits formed by the rearrangement under water of any of the preceding forms, known as Rearranged or Modified Glacial Beds. Each of these forms has certain peculiarities of its own which enable us to distinguish it from the others of its class.

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* This term is often used loosely for any form of glacial deposit. It may be conveniently restricted to the meaning assigned to it in the text.

Till.—Till is a deposit of excessively tough dense clay, stuck as full as it can hold of stones of all sizes, which are not arranged in any order, but look as if they had been forcibly rammed in anyhow, and are mixed big and little indiscriminately together. Where it has to be cut through, it is more difficult to master than the hardest rock; it can be neither broken nor blasted, and has to be laboriously worked away by spade and mattock. Every navvy, who has to deal with it, soon learns to recognise its formidable nature, and becomes as good a judge of what ought to be called Till as the most accomplished geologist. The stones are many of them angular or have their edges and angles slightly blunted, and a very large proportion of them show ice-scratching and polishing. The materials of which Till is composed are very largely derived from the rock on which it rests or from rocks in its immediate neighbourhood; thus the Till of a country composed of dark clayey rocks will be dark in colour and very stiff; where the underlying beds are of red sandstone, the Till will be reddish and lighter in character, owing to an admixture of sand.

Wherever Till is found there is always independent proof that the country has been covered by a sheet of continental ice. We have already seen that under such a sheet there is probably formed an accumulation of clay and stones known as Moraine Profonde or Grundmorane, and Till resembles exactly what we picture to ourselves that this deposit must be like. There would be weight enough above to give rise to the intense toughness and the close and irregular packing of the stones, and the scratching and polishing would be produced as the mass was pushed hither and thither by the flow of the ice. Such an explanation accords also well with the local character of Till.

Hence, though the existence of the Moraine Profonde is to a certain extent hypothetical, the probability that such an accumulation is formed beneath large ice-sheets is so great, and its character, if it exist, must be so exactly that of Till, that nearly all geologists are now agreed to look upon the latter as having been formed by the grinding and wearing away by an ice-sheet of the ground on which it rested.

Another explanation of the origin of Till has lately been propounded by Mr. Goodchild (Quart. Jour. Geol. Soc., xxxi. 75—98). He thinks that the materials of which Glacial Deposits are composed were originally embedded in the ice-sheet, and that when the ice melted its contents were gradually set free; some were merely dropped, others more or less sorted and arranged by streams running below the ice; and in this way he suggests many, if not all, of the various forms of Glacial Deposits may have been produced by the one single operation of the melting of the ice. Whether we agree or not with Mr. Goodchild's conclusions, his paper will probably lead us to think that the explanation of the origin of Glacial Deposits is not altogether so simple a matter as some people have supposed, and that there are many points connected with the subject that still want clearing up.

Though one of the distinguishing characteristics of Till is the preponderance of stones belonging to the immediate neighbourhood where it occurs, the reader must not suppose that fragments of rock which have come from distant localities are altogether wanting in it. It is by no means uncommon to meet with far-travelled stones in Till, but, as a rule, they form only a minority of its contents. Further, these strangers are frequently found at much higher levels than the rock from which they were broken off. For instance, the Till of the Vale of Eden contains, besides the rocks of the valley itself, many that have come from the Lake country, and even a sensible proportion of stones that have travelled from the opposite coast of Scotland; and these foreign materials, with others that have come from the low parts of the valley, can be traced up to the summit of the pass of Stainmoor.* Both the presence of stones from a distance and the elevation at which they occur are easily accounted for. The gathering ground, from which the ice-sheet that produced the Till started, was a long way off, and on its journey the ice picked up samples of the different kinds of rocks it passed over; these travelled on with the ice, carried on its surface or frozen into its mass, and were dropped wherever they were set free by melting or any other cause. Again, ice-sheets we know in many cases pursue their course with but little regard to the shape of the ground, are driven *across* valleys, and forced *up* the slopes of hills, and in this way it frequently happens that the stones and boulders they carry are stranded at spots very much higher above the sea level than the source from which they were derived.

Moraines.—Moraines resemble Till in consisting of a confused mass of stones and earth: the whole is jumbled together in a pell-mell way without regard to size, shape, or weight, somewhat in the same way as the heaps of rubbish "tipped" to. form a railway embankment. The main points of difference are these. In a Moraine the great mass of stones have ridden on the top of the ice, and hence, though they will be mostly sharp and angular, but few will be polished or scratched. Moraine matter too having been merely shot on to or over the end of a glacier, and not pressed down by the weight of the ice, will not possess the characteristic denseness of Till. The external shape of Moraines is also peculiar: they form mounds, arranged in long lines along the flanks of a valley if the Moraine be longitudinal, or stretching in horseshoe-shaped courses across a valley, if it be terminal.

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* Goodchild, Quart. Jour. Geol. Soc., xxxi. 66, 67; J. Geikie, Transactions Geol. Soc., Glasgow, iv. 235.

Both Till and Moraines agree in being perfectly unstratified, and differ in this respect from the other forms of ice deposit.

Glacial Mud.—From beneath every sheet of ice there issue streams of water loaded with an impalpable mud, the finer part of the matter ground by the ice from the rock over which it moves. When this sediment is thrown down beneath still water, it forms silty and clayey deposits of unusual fineness. The water into which glacial streams flow is too much chilled to allow of any but animals that can bear cold existing in it, and hence the fossils that occur in these clays are northern forms. Occasionally too floating ice will drop angular stones and boulders among the fine silt. A deposit then of very fine mud, containing the remains of animals that inhabit northern waters and angular blocks of rock, may safely be set down as having been formed out of sediment deposited by streams discharged from beneath a sheet of ice.

Boulder Clays.—Under this head we may include deposits formed beneath water, partly out of sediment held in suspension, and partly out of the droppings of floating ice. Such accumulations will be more or less bedded, but they may be distinguished from those stratified deposits, in whose formation ice had no share, by the large angular travelled blocks which are embedded here and there in them. The beds of these deposits are often bent and twisted into very complicated curves. This result seems to have been produced partly by the stranding of icebergs, which, after they had run aground and ploughed into the bottom, were driven on by currents; partly by the melting of masses of ice buried in the middle of a body of Boulder Clay, by which the beds above were deprived of support and caused to sink down into the cavity produced by the removal of the ice-block.

Erratics and Perched Blocks.—We next come to those large blocks, often met with lying on the surface, which are known as *Erratics* or *Wandered Stones.*[*] When we can determine by any peculiarity in the rock the locality from which they have come, these Erratics are often found to have travelled far from their home, and in spite of their long journey to be angular or only very slightly rounded. This circumstance, leaving out of consideration their great size, makes it impossible that they can have been brought by water, and ice is the only agent that could have carried them. Some of them have been dropped from icebergs when the ground where they occur was beneath water: others have been carried on the back of an ice-sheet, and stranded when the ice melted away. The latter are sometimes found in positions in which it seems at first sight quite impossible that they could have come by natural means, delicately poised on their smaller end, or balanced on the top of some projecting crag: these are called *Perched Blocks.* They have been gently let down into their present strange positions by the gradual melting away of the ice beneath them. Fig. 26 shows a Perched Block resting on a surface of rock that has been smoothed by ice.

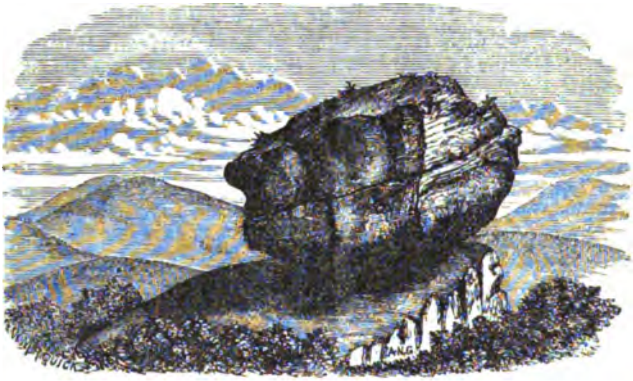

Fig. 26.—Perched Block.

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[*] The Germans call them Foundlings (Findlinge).

Rearranged Glacial Beds.—All the preceding forms of glacial deposits are liable to be worked up and carried away by denudation, and either considerably modified on the spot, or carried off and redeposited elsewhere. By such means, specially if they are transported to any distance, glacial formations lose much of their distinctive character. The angular stones become rounded, the large boulders are broken up, and the scratchings and polishings are worn off. But the peculiarities we rely upon as indicating a glacial origin are not always completely wiped out, indistinct traces of ice-scratchings for instance often survive a good deal of wear and tear. By attending to such points we can often determine that a deposit, though it may have passed through various changes before it assumed its present form, was originally derived from a mass of ice-formed debris.

Rocks and Deposits of Glacial Origin.—There is a large body of deposits, of immense antiquity historically, but young compared with the mass of the rocks of the earth's crust, in whose formation ice has been in one way or another concerned. Till occurs abundantly in North Britain, Scandinavia, North America, and many other districts, and shows that these countries were once buried under sheets of continental ice. The Moraines of vanished glaciers are plentiful in many hilly and mountainous districts from which all traces of snow are now cleared off every summer; and even in those regions, like the Alps, which still nourish perpetual snow, there are Moraines which show that the glaciers were formerly far larger than now. Associated with these indications of a former severity of climate are subaqueous Boulder Clays and deposits of Glacial mud.

It is evident that all glacial formations are somewhat restricted in extent, and that the terrestrial forms are very likely to be carried away by denudation, and we should not therefore expect to find very abundant traces of them among the older portions of the earth's crust. Even here however there are Conglomerates and Breccias which there is every reason to look upon as consolidated Tills or Boulder Clays, on account of the close resemblance they bear to these deposits.

SECTION VI.—HOW SEDIMENT IS COMPACTED INTO ROCK.

So far we have found a most perfect agreement, both in broad general character and in the minuter details of structure, between the deposits now forming by the action of denudation beneath water or on dry land, and certain of the rocks of the earth's crust. All the principal kinds of the deposits that are now forming have been passed in review, and to every one we have been able to find a parallel in the class of rocks. In one respect however the two classes will usually be found to differ. Modern deposits are mostly loose and incoherent, and rocks as a rule hard and compact. To this statement there are many exceptions, but still it is true in so large a number of cases, that we must, if we would make good the original identity of rock and sediment, explain how the latter can be compacted into the former. Any little difficulty, that this seeming want of agreement may at first sight cause, will vanish, if we reflect that, if rocks were formed in the way suggested, their formation took place long ago, in many cases very, very long ago indeed, and if we turn over in our minds all that has happened to them since that date. The following are some of the principal causes that have had a share in the conversion of loose sediment into hard rock.

Weight of Overlying Masses.—In the first place when layers of sediment have been placed one on the top of another till the pile reaches a great thickness, the mere weight of the mass must compress and harden the lower portion. It is this lower part we see now, for the upper beds have been removed by denudation. This cause alone would account in many cases for the solidification necessary to convert sediment into rock.

Deposition of Cement.—Masses of loose sediment are also traversed by percolating water, which holds in solution substances such as Carbonate of Lime or Silica. These dissolved matters will, if deposited by evaporation or any other means, act as a cement and bind the loose particles together.

Chemical Reactions.—Chemical reactions too go on among the constituents of sediment, and produce solidification. It is possible for instance that some soft deposits may, on drying, "set," like mortar or plaster of Paris.

Internal Heat.—We shall learn by-and-by that the interior of the earth is very hot, and we have already seen that in many cases during the deposition of sediment the mass must have gone on sinking deeper and deeper into the ground. In this way it may be brought within the range of this internal heat, and baked. The same process must go on in the neighbourhood of active volcanoes, though in this case the effect will probably be local. This solidifying cause will be more fully considered under the head of Metamorphism.

Pressure.—But perhaps the most important agent in the consolidation of sediment into rock is one whose action we can only partly explain here. It will be shown by-and-by that beds of mechanically formed rock are seldom found in the horizontal position in which they were originally deposited. They have been tilted so as to lie at all angles with the horizon, and, what it more especially behoves us to notice in connection with our present subject, they have often been bent and folded into the most complicated curves.* A change in position like the latter can evidently have been brought about by nothing but forcible lateral pressure; and we shall also see, when we come to consider these disturbances more fully, that, at the time when it was produced, the beds were not at the surface, as we see them now, but were loaded above by the weight of a great thickness of overlying rock, which has since been removed by denudation. Now it is just these powerfully folded beds, which have been not only subjected to intense lateral compression, but also pressed forcibly from above, that are the most intensely hardened. In Russia† and North America there are rocks of great antiquity, which are so little changed from the condition in which they were originally laid down, that a very slight amount of weathering is enough to reduce them to their pristine state of mud, and which are hence called "mud stones." *But these rocks have been scarcely disturbed at all from the horizontal position in which they were formed.* On the other hand there are beds, in the Alps for instance, immeasurably younger, which have been solidified and even rendered crystalline to such a degree, that they were for a long time assumed, in virtue of their intensely hardened state, to be of very remote date. *But these rocks are invariably violently contorted.*

We may therefore lay it down as a broad general truth, that pressure and consolidation go together; and that, where there is an absence of consolidation, there has been also an absence of pressure. Hence pressure must be looked upon as one of the most important agents, perhaps the most important, in the conversion of loose sediment into firm rock.

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* See Chapter ix.

† Russia and the Ural Mountains (Sir R. I. Murchison), i. 78.

It is also possible that pressure, when it could effect no further mechanical compression or change of position in a rock, may have appeared as heat, and so helped on the work of consolidation.

These agencies are fully competent to effect the conversion of loose sediment into firm rock, and any sediments that were formed at bygone periods of the earth's history must have been subjected to the action of one or more of them. The only hitch in our line of reasoning has now been removed, and the conclusion is irresistible that *the bedded rocks of the earth's crust were once of the same nature and origin as these modern deposits, which they resemble in every respect, except occasionally that of hardness.*

We may safely lay it down as a general rule, that, in a number of rocks having the same mineral composition, the oldest will probably be the most solidified; because, the older a rock is, the greater chance will it have had of having been subjected oftener and for a longer time to pressure and other consolidating influences. But exceptional cases, like the two mentioned a little way back, are numerous enough of rocks, on which time and its accidents have wrought scarcely any change whatever, and which now stand before us very nearly as they were spread out on the floor of the ocean untold ages ago.

SECTION VII.—SOME STRUCTURES IMPRESSED ON ROCKS AFTER THEIR FORMATION.*

Besides the different kinds of bedding, which are a necessary consequence of the way in which the stratified rocks were formed, there are other peculiarities of structure, which have been produced in rocks since their formation. Three of these, Cleavage, Jointing, and Concretions can be understood by any one who has mastered the contents of the preceding part of this book, and may therefore be conveniently treated of here. Others of the structures impressed on rocks subsequently to their formation will be explained further on.

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* In connection with the subject of this section, the student will do well to study Professor Sedgwick's paper, "On the Structure of large Mineral Masses," Transactions Geol. Soc. London, 2nd series, iii. 461.

Structural peculiarities of this class are not confined to any one class of rocks, but are found in the stratified and unstratified alike.

Cleavage.—We will begin with Cleavage, because the cause to which it is due is that Pressure which we have just been talking about as one of the agents that have hardened rocks.

In most cases bedded rocks split readily along the planes of bedding: but instances are not uncommon of rocks, which are evidently bedded, but which cannot be induced by any means to part along the planes of bedding, while they split readily along a number of other planes, which are often smooth, regular, and close together, so that the rock can be broken up almost without limit into thin plates or laminæ. Roofing Slate furnishes the best possible instance, and one which any one may verify for himself.

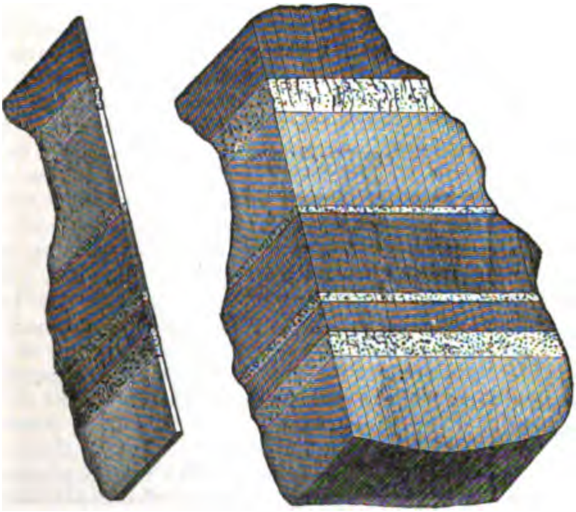

Fig. 27.—Cleavage and Bedding.

This structure is called *Cleavage*, and the planes of division *Planes of Cleavage*.

Fig. 27 is a representation of a bit of cleaved rock. The bands of different shade and pattern are layers of different colour, hardness, and mineral composition; and the close resemblance which these show, when the mass of the rock is studied, to layers of stratification, leaves no doubt on the mind that these are the layers in which the rock was originally deposited. We can however no longer separate these layers from one another, they are firmly welded together.* But a set of fine lines are seen crossing the face of the block; these are the edges of planes of cleavage, and along them the rock splits up readily into thin plates, one of which is shown in the drawing.

The labours of several observers have given a satisfactory explanation of the origin of cleavage. It was noticed that fossils in cleaved rocks were distorted from their natural shape, and that the distortion did not take place at random, but always in the following manner: *they were squeezed flat perpendicular to the planes of cleavage, and spread out along those planes.* In Fig. 28 *a*, for instance, we have a section of a limestone containing stems of encrinites, which are cylinders, and show their normal circular section; Fig. 28 *b* shows a section of a similar limestone, which has been cleaved; here the stems are flattened, and the sections of them are ellipses with their longer axes parallel to the planes of cleavage. A microscopical examination of thin sections of cleaved rock shows that the minute particles of the rock are flattened in a similar manner.

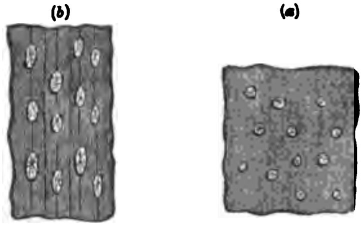

Fig. 28.—Section of Rock before and after Cleavage.

These observations showed that *cleaved rocks had been compressed in a direction perpendicular to the planes of cleavage;* but they did not prove that pressure was the cause of cleavage.

That final step in the argument was supplied by Mr. Sorby, and afterwards by Prof. Tyndall, both of whom produced cleavage artificially in sundry substances by subjecting them to pressure, and found that the cleavage planes were always perpendicular to the direction of the pressure. Every step in the argument was now complete, and no doubt remained that *a cause of cleavage was pressure acting at right angles to its planes.*

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* This, though very generally, is not universally the case: some cleaved rocks may still be split along their planes of bedding. See Jukes, Report on the Geological Survey of Newfoundland, p. 75.

No other means of producing cleavage has yet been hit upon, and therefore we refer all cleavage to this cause.*

A study of cleavage on a large scale confirms this conclusion. Cleavage always goes along with that bending, folding, and puckering up of the rocks, which has been already mentioned; and it is found that *the direction of the planes of cleavage is always parallel to the axes of the large folds into which the rocks have been thrown.*

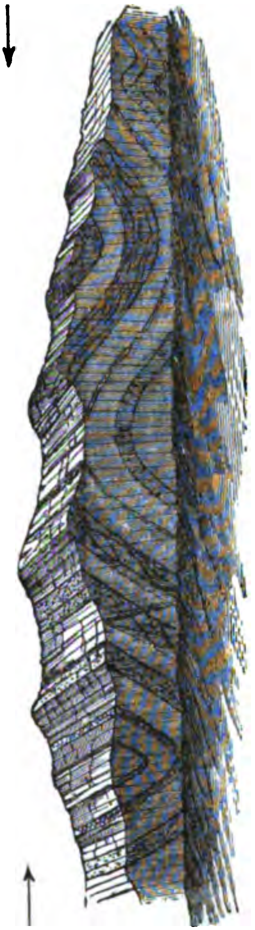

Fig. 29.—Cleaved and Contorted Rocks, showing a parallelism between the planes of cleavage and the axes of the folds.

Fig. 29 is a bird's-eye view of a country of contorted and cleaved rock terminated by a cliff in the foreground; on the face of the latter we see both the folds of the rocks and also the edges of the planes of cleavage, which are denoted by the fine vertical lines. The trend of the cleavage planes is shown across the country by continuations of these lines, and the directions of the axes of the folds by the range of the several beds as they come one by one to the surface: and these two directions have the same bearing.

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* We must not however lose sight of the possibility of galvanic currents causing a laminated structure. See the experiments of Mr. R. W. Fox and Mr. T. Jordan, Reports of the Royal Polytechnic Soc. of Cornwall, No. 5, 1837, p. 68, and No. 6, 1838, p. 169; and of Mr. R. Hunt, Memoirs of the Geological Survey of England, i. 433.

Now the pressure that produced the folding must have acted perpendicular to the axes of the folds, in the direction shown by the arrows at each side of the diagram: and since the axes of the folds and the cleavage planes run parallel to one another, this is the same thing as saying that the cleavage planes are perpendicular to the pressure, to which the bending of the rocks shows them to have been subjected.

The cleavage planes are smoother, truer, more regular, and closer together in finely grained homogeneous rocks than in those of coarse composition. Thus in Fig. 27 the dotted belts are coarse and sandy, the tinted beds fine slate; the cleavage planes when they enter the former become irregular, are sometimes deflected a little, and sometimes lost altogether, as in the very coarse bed at the bottom.*

The student must not confound the cleavage of rocks with that of crystals. The two have points of resemblance, so much so that it was once conjectured they might be due to the same cause. But they are essentially different, the one being a result of mechanical, the other of molecular forces.

Jointing.—Some rocks, which go by the name of Freestones, can be cut with equal ease in all directions perpendicular to their planes of bedding; and some of these are so valuable, that it is desirable in working them to extract the blocks as near as may be of the size and shape as will be wanted, and so save loss in dressing. In this case the quarryman cuts out the pattern of his stone by picking out a shallow groove on a plane of bedding: into this groove he inserts short thick wedges, and by driving these down produces cracks, perpendicular to the planes of bedding, by which the block is detached. But if the only object is to get stone out, without being particular as to the size and shape of the blocks, all this trouble may be saved, for nature has in most cases provided cracks ready to hand of exactly a similar kind.

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* On Cleavage, see Sedgwick, Transactions Geol. Soc. of London, 2nd series, vol. iii. p.479; Rogers, Transactions of the Royal Soc. of Edinburgh, xxi. 447; Baur, Karstens u. v. Dechens, Archiv, xx. 398; Phillips, Reports of British Association, 1843, p. 60; 1857, p. 386; Darwin, Geological Observations on South America, chap. vi.; Rogers, Edinburgh New Phil. Journal, vol. xxxiii. p. 144; Sharpe, Quart. Journ. Geol. Soc. of London, vol. iii. p. 74, vol. v. p. 111; Phil. Transactions, vol. clxii. p. 445; Hopkins, Cambridge Phil. Transactions, viii. 456; Sorby, Edinburgh, New Phil. Journ. vol. lv. p. 137; Phil. Mag. 4th series, vol. xi. p. 20, vol. xii. p. 127; Tyndall, Phil. Mag., 4th series, vol. xii. p. 35 and 129; Haughton, ditto, p. 409; D. Forbes, Popular Science Review, 1870, p. 8. It will be seen by reference to the above papers that the steps by which a knowledge of the cause of cleavage was arrived at were as follows:—First, the discovery of the parallelism between the strike of the beds and that of the cleavage planes; secondly, the observation of the flattening of fossils and particles perpendicular to the cleavage planes; thirdly, the artificial production of cleavage. The arrangement in the text has been adopted because it seemed to bring out the logical steps in the train of reasoning better than the order of discovery.

These planes of division, which are found in all rocks that have been to any extent consolidated, are known as "*joints*." By means of them, and the planes of bedding if the rock be bedded, it is cut up into ready-made blocks, whose size and shape depend on the arrangement of the bedding and joint-planes. Joints are noticeable in quarries, because in most cases the stone is worked off along these natural cracks, and they come to form the walls of the excavation; they also often form the faces of natural crags, cliffs, and precipices.

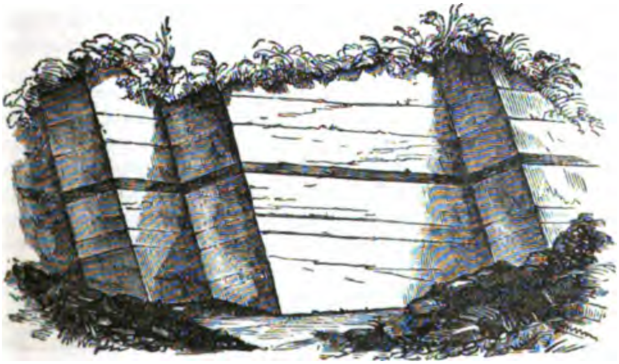

Fig. 30.—QUARRY IN JOINTED ROCK.

Fig. 30 shows a quarry where the joints are very regular and conspicuous. The nearly horizontal lines are the edges of the planes of bedding. The faces, on which the light falls, are made by a set of joints nearly parallel to another, which traverse the body of the rock with great uniformity of trend; another set of joints, also regular and parallel to each other, but at right angles to the first set, form the faces in shadow.

Jointing of this regular character is mostly found in hard rocks of homogeneous composition, such as Limestones and thickly bedded Sandstones. There are in such cases usually two sets, the joints of each being roughly parallel to one another, and the bearing of one set is generally not far from perpendicular to that of the other set. As a rule one set is characterised by greater regularity of direction, and by its joints being continuous for longer distances, than the other set. The more regular set generally, in the case of bedded rocks, ranges parallel to the strike and the other set to the dip* of the beds.

Joints, which keep the same direction for long distances and run through a great thickness of beds, are called "Master Joints."

But in many cases joints show no such symmetrical arrangement as that just described. They cross each other in all directions, change their bearing, and instead of running through a great thickness of beds, are confined to one bed, or change their inclination and direction in passing from bed to bed. We also find frequently joints running in more than two directions, which cut up the rock into prismatic masses having a triangular or polygonal section: it is by joints of this character that the striking columnar structure of Basalt is produced. The instances of the Giant Causeway and Staffa are familiar to everybody. But we shall return to this in Chapter VI.

The faces of most joints are approximately plane, but we occasionally find joints with curved faces, giving rise to masses of rock with an outline like that of the side of a ship.

Jointed structure is shown perhaps nowhere so distinctly as in some kinds of Coal. If a block of Coal be examined, it will usually be found to be divided into a number of laminæ by planes parallel to the upper and under surfaces of the bed: the bed splits readily along these planes, and the surfaces of the laminæ are generally dull, soft, and sooty: but the block will also be found to be cut across by two other sets of parallel planes of division, perpendicular to the bedding, and roughly perpendicular to one another, and the surfaces of these planes are brighter and smoother than those of the laminæ. The planes of one set are more regular, true, and perfectly formed than those of the other set. In some cases these three sets of divisional planes cause the bed to break up into small cubical blocks of so regular a shape as to give one the idea that the Coal is really crystallised, such Coal is known as "Dicey Coal." There is a limit however beyond which the subdivision cannot be carried, and this is not the case with truly crystallised substances; and, though, may be, it is not always possible to say where jointing ends and crystallisation begins, it is safer to look upon this structure as jointing, which has been very completely and minutely carried out because the Coal is of fairly uniform composition throughout. The more regular set of joints is known as "the face," "slyne," "cleat," or "bord;" and the other set as "the end." The compass bearing of the face often remains exactly the same over very large areas. This structure is of the utmost assistance in working Coal; the main roads or galleries are, whenever it is practicable, driven along the "bord," and the cross cuts which connect them along the "end," the first being called "bord gates," the second "endings:" in some cases it is necessary to drive *across* the "face," but such an operation involves an increase of labour and expense, because the walls of the road are no longer formed by natural planes of division, but have to be hewn across solid Coal.

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* For an explanation of these terms, see Chapter ix.

No very satisfactory explanation has yet been given of the cause which produced jointing. In some cases perhaps joints are of the nature of shrinkage cracks, caused by the contraction of the rock as it dried, hardened, or, in the case where it consolidated from a fused state, cooled; something in fact like the cracks seen on the surface of recently dried mud, or the cracks which are so liable to ruin large castings in metal.

The force that produced jointing must in some cases have been very considerable. In some Conglomerates the hardest pebbles are cut through by joints, as neatly as if they had been sliced by a lapidary's wheel; and this occasionally occurs where the matrix has been very slightly consolidated. It can hardly have been contraction that produced these joints, for the result could have been brought about only by some force which found it easier to divide a pebble than to draw it out of the matrix. It is open to question whether divisional planes of this kind are not akin to cleavage, and whether it is always possible to distinguish with certainty between jointing and cleavage.

There is also, as we have noticed in the case of Coal, sometimes a resemblance between very minute jointing and the cleavage of crystallised substances; the two however may be distinguished in this way: there is no limit to the extent to which cleaved crystals may be again and again subdivided; however small for instance may be the rhombohedron of Calcite we have obtained by cleaving a crystallised mass of that mineral, we can always break it up into similar smaller rhombohedrons, and we can carry on this process of subdivision till the resulting crystals cannot be recognised even by our most powerful microscopes, and then see no reason to think we have reached a limit; but however close or numerous may be joints, we always arrive sooner or later, as we go on subdividing a jointed rock, at a piece of finite size with no more joints in it. Still however in some rocks, which consist largely of a mineral which crystallises readily, the tendency of that mineral to assume a definite form, may have had something to do with the direction of the joints, and caused them to arrange themselves rudely parallel to the faces of that form. Thus in the well-known Sandstone of Fontainebleau, which consists of Sand cemented by Carbonate of Lime, the tendency of the latter to crystallise in rhombohedrons has given rise to a series of joints, which divide the rock into rhombohedral masses having the same angles as the fundamental form of Calcite: but these masses cannot like the Calcite crystal be indefinitely subdivided into similar rhombohedrons.*

On the subject of jointing the reader may consult the following papers:—

Sedgwick: Transact. Geol. Soc. of London, 2nd ser. vol. iii. 461.

Phillips: Reports of British Association, 1834, p. 654.
,, Transact. of Geol. Soc. of London, vol. iii. p. 1.
,, Phil. Mag. and Annals, vol. iv. p. 401.

Hopkins: Report of British Association, 1838, p. 78.

De la Beche: Geological Observer, p. 718.

Harkness: Quart. Journ. Geol. Soc. of London, vol. xv., p. 87.

Haughton: Phil. Transact., vol. cxlviii. p. 333.

The Geology of North Derbyshire and the adjoining parts of Yorkshire (Memoirs of the Geological Survey of England), p. 143.

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* See Naumann's Lehrbuch der Geognosie, i. 485, for references; also Gages, Reports of British Association, 1863, p. 207.

Explanations of Sheets 114, 122, 123, and 184 of the maps of the Geol. Survey of Ireland.

Concretions.—Balls, lumps, or nodules, of different composition from the rocks in which they are found, are common in many rocks. They are quite distinct from the pebbles in conglomerates, which were, at the time of the formation of the rock, pebbles just as they are now. The balls we are now speaking of have been formed since the rock, in which they are embedded, was deposited: we know this, because in many cases the lines of bedding of the adjoining rock can still be traced running through the nodule, as in Fig. 31; and, in the case of fine clayey rocks, the laminæ do not bend up round the nodule, as would have been the case if it had lain as a lump at the bottom of the water from which the sediment was thrown down. Nodules of this kind are of various shapes;* sometimes spherical, at others of fantastic forms, but always with a rounded outline: sometimes they are made up of a number of concentric coats, like an onion; sometimes they have a radiated structure, *i.e.* they consist of long slender fibres radiating from a common centre; sometimes the concentric and radiated structures occur together. A very common form, known as a Septarium, shows inside cracks and cavities, largest towards the middle and not extending to the surface, filled up with a crystallised mineral. It very frequently happens that in the middle of a nodule there is a shell, plant, fish, or grain of sand: and the shape of this nucleus has evidently determined the external form of the nodule.

Fig. 31.—Concretions with Lines of Bedding running through them.

The arrangement of these nodules generally bears some relation to the stratification, and frequently they are grouped along the planes of bedding, probably because certain beds contained the ingredients necessary for their formation, while other beds did not.

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* For a good group of figures, see Dana's Manual of Geology, p. 96.

As instances of concretions we may mention Flints in Chalk, and the balls of Iron Pyrites and of Clay-ironstone which are common in clayey strata.

The fact that nodules have been formed since the deposition of the rocks in which they are inclosed, and that they have in many cases been moulded round some body which now forms their heart, leads us to the conclusion that the matter of which they consist was once disseminated through the body of the rock in which they occur, and has been afterwards separated out and gathered into balls. We can even in some cases trace to a certain extent the steps of the process. The early stages seem to be marked by extended lines of flattened nodules, forming broken beds: a further concentration of the segregated matter gave rise to lumps more spherical in shape; and occasionally a contraction of the interior, after an outside solid crust had been formed, produced the cracks of the Septaria, in which percolating water deposited a crystallised lining.*

There can be little doubt that the explanation just given of the method of growth of concretions is true of Chalk Flints. From what is known about the state of the present bed of the Atlantic, it is probable that, side by side with the calcareous Foraminifera, which furnished the material for the Chalk, there lived siliceous Foraminifera, Sponges with siliceous spiculæ and framework, and other silica-extracting animals. The hard parts of all these creatures, calcareous and siliceous alike, accumulated on the sea-bottom, and produced a calcareous mud, with which siliceous particles were intimately mixed: at some after period the siliceous element was separated out from the mixture and aggregated into balls, a sponge or some other body often furnishing a centre round which the aggregation took place.

It has been observed in laboratory experiments that, when different substances in a state of fine division are mechanically mixed together, certain of them do separate out and congregate together into nodular masses,† and it has been noticed that nodules are being formed in the same way in some rocks now in the course of deposition. It is usual to speak of this process as Concretionary Action.

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* De la Beche, Researches in Theoretical Geology, p. 96.

† Babbage, Economy of Manufactures, 2nd ed. p. 50.

There is no objection to be raised to this phrase, and it, or some similar term, may be safely and conveniently used to express the fact that certain matters have been separated out of the body of a rock and collected together in balls, provided always we bear carefully in mind that, by giving the process a name, we do not get any nearer to understanding the manner in which the result has been brought about. If any one asks us what made the nodules, we may, if we like, say Concretionary Action; but if the awkward question is put, what is Concretionary Action, we should be somewhat puzzled for an answer. We know that one of the ingredients of a mixture has been extracted from the surroundings and gathered into lumps: how exactly this was done we don't know. The term in fact is only a way of stating our ignorance; and, unless due precaution be taken, a somewhat dangerous way, because to certain minds it looks like an explanation.

Concretionary Structure in Rocks.—Rocks themselves sometimes put on a concretionary structure on a large scale.

A classical instance is the Magnesian Limestone of Durham, described by Prof. Sedgwick. This rock, in the neighbourhood of Sunderland, is entirely made up of rounded nodular masses, and when these are loosened by weathering, it has the look of a pile of rudely-shaped cannon-balls. So complete is the separation into nodules that the rock might be mistaken for a conglomerate, if it were not that the lines of bedding can still be traced running through the balls and the body of the rock alike.*

Fig. 32 shows a case of large concretions in Sandstone, where the process seems to have been imperfectly carried out.

Some of the most striking instances of concretionary rocks occur among those which have consolidated from a fused state. These will be noticed under the description of such rocks.

Oolitic Structure.—There is another somewhat allied structure, which may be noticed here.

Many rocks, especially limestones, are made up of rounded particles varying in size from a pin's head to a pea. There is generally some little foreign body, a grain of sand or a fragment of shell, in the middle of each ball, round which aggregation has taken place. Such rocks, when the granules are small, are called Oolites or Roestones from their resemblance to the roe of a fish: the coarser varieties are called Pisolites, or Peastones. We have already mentioned that this structure has been observed in Limestones now forming on the beaches of Coral islands out of the debris of Coral rock. In some cases it is possible to watch the way in which little grains act as nuclei, and become coated over with successive shells of Carbonate of Lime, and so enlarged into minute concretions.* In such cases the aggregation of the mineral goes on at the same time as the formation of the rock, and the concretions formed differ in their mode of growth from those in which the process of separation and aggregation took place after the formation of the rock was complete.

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* Sedgwick, Transactions Geol. Soc. of London, 2nd series, iii. 94 and 465. See also De la Beche, Memoirs of the Geological Survey of Great Britain, i. 43, for another instance.

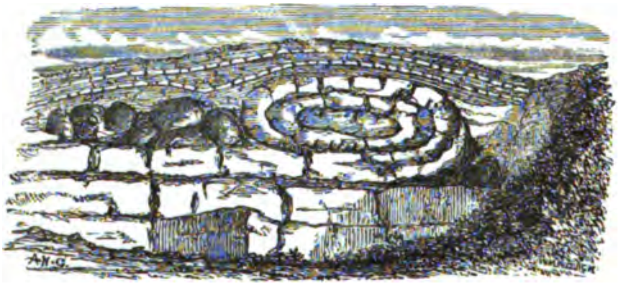

Fig. 32.—CONCRETIONARY STRUCTURE IN SANDSTONE.

Secretionary Nodules.—There is a class of nodules which it is desirable to distinguish from concretions, because they have arisen in a different manner. Like some concretions they are rounded and consist of concentric coats; but when they contain a hollow space inside, as is often the case, its walls are frequently lined with crystals having their vertices or bright faces *turned inwards*. This last fact shows that the formation of such nodules has gone on *from without inwards*, whereas concentric concretions were formed in the opposite direction, by the successive growth of coat over coat from a central nucleus outwards.

Nodules of this class may be called Secretionary or Incretionary: they have been formed by the deposition of mineral matter from percolating water in hollow spaces in rocks: the first coat was laid down on the walls of the cavity, upon the inner surface of this another coat was deposited, and so the growth of the nodule has gone on in the direction just mentioned. Agates are a common instance of this class of nodules.

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* Dana, Corals and Coral Islands, p. 153.

CHAPTER V.

DEFINITION AND CLASSIFICATION OF DERIVATIVE ROCKS; AND HOW FROM A STUDY OF THEIR CHARACTERS WE CAN DETERMINE THE PHYSICAL GEOGRAPHY OF THE EARTH AT DIFFERENT PERIODS OF ITS PAST HISTORY.

> "In these shows a chronicle survives."
>
> WORDSWORTH.

OUR task in the last chapter was to inquire how the waste resulting from denudation is disposed of. We found that by far the larger part of it is ultimately laid out on the floors of bodies of still water; and that the deposits now forming in this manner, though they differ from one another in many respects, all agree in possessing a bedded or stratified structure. We have already learned that a large class of the rocks of the earth's crust are characterised by a like bedded arrangement.

Here then we had one point of resemblance between certain rocks and deposits now in the course of formation, and, when we came to examine the latter more in detail, it was seen that the agreement between the two was not confined to bedding; in fact as each kind of modern deposit was passed in review, we were able to point to some one or more of the rocks of the earth's crust, from which it differed in no respect whatever, except in certain cases that of consolidation.

We were thus irresistibly led to the conclusion that bedded rocks were formed in exactly the same way as those modern deposits from which they differ in no essential respect. Having now learned how bedded rocks were produced, we can substitute for our former threefold subdivision of them into Arenaceous, Argillaceous, and Calcareous, a more complete classification, which will have respect not only to what these rocks are made of, but to the way in which they were formed.

Derivative Rocks and their Classification.—The rocks hitherto treated of owe their origin directly or indirectly to denudation, and hence they may be all classed together as "Derivative."

We may subdivide them, according to the *manner* of their formation, into—

1. Mechanically formed.
2. Chemically formed.
3. Organically formed.

The first are formed of mechanically transported sediment: the second and third out of the matter carried down in solution, which is sometimes precipitated chemically, and sometimes extracted by the agency of animals or plants.

If we look to the *circumstances* under which Derivative Rocks were formed, we may class them as follows:—

1. Marine: formed beneath the waters of the sea.
2. Estuarine: formed at the meeting of fresh and salt waters.
3. Lacustrine: formed in inland bodies of water.
4. Terrestrial: formed on land.

Under the first head we shall have to distinguish between *Littoral* deposits, or those formed near the shore: the deposits laid down on parts of the sea-bottom remote from land, but still near enough to it to receive mechanical sediment, which may be called *Thalassic;* and those produced at spots so far from land that little or no mechanically carried sediment finds its way to them, which may be called *Oceanic.*

There will be two classes of Lacustrine deposits, those formed in fresh, and those in salt water.

Terrestrial deposits are formed mainly by atmospheric weathering, by wind, by vegetable growth and decay, and by the action of ice.

The fossil remains of animals and plants preserved in rocks often give a clue to the circumstances under which the latter were deposited. The study of fossils or Palæontology will form the subject of a future chapter, but we shall point out here the aid they give in the matter of our present inquiries.

The foregoing considerations lead us to some such broad general classification of the Derivative Rocks as is given in the following table.*

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* Compare Geological Magazine, v. 503.

General Classification of Derivative Rocks.

A. Marine.	*Littoral.*	Mechanical. Sandy and coarse. Variable in horizontal range and irregularly bedded. Ex. Conglomerates and Coarse Sandstones.
	Thalassic.	Mechanical, or mixed mechanical and organic. Clayey and fine. Constant for large horizontal distances and regularly bedded. Ex. Fine Sandstones, Shales, and impure Limestones.
	Oceanic.	Organic. Calcareous. Often of great horizontal extent. Ex. Pure Limestone. Altered Organic deposits. Ex. Atlantic Red Mud.
B. Estuarine.		Mechanical. Sandy and clayey Rocks, and impure Limestones. Irregular bedding with frequent changes in mineral composition. Alternations of marine, brackish, and fresh-water beds. Marine fossils often dwarfed.
C. Lacustrine.	*Freshwater.*	Mainly sandy and clayey beds and impure Limestones of mechanical origin. Organic or semi-organic occasionally. Some chemical precipitates of Carbonate of Lime and Silica.
	Saltwater.	Chemical Precipitates, such as Rock Salt, Gypsum, and Dolomite, conspicuous; occurring in lenticular masses among sandy and clayey mechanical deposits. Fossils rare, sometimes stunted and deformed marine forms.
D. Terrestrial.		*Mechanical.* From atmospheric weathering, Rainwash, Screes, Old Soils. From wind (Æolian), Blown Sand. *Organic.* Mainly of vegetable origin, as Coal.* Animal deposits of Guano.

N.B.—Deposits formed by the aid of ice are omitted from the above table for reasons given on p. 182.

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* It is very convenient to put these rocks here, though they have scarcely a right to the place, unless we stretch a point

One word of warning about the last column of the above table. Its object is not to specify every single one of the different kinds of rock which are somewhere or other to be met with in each subdivision; but to point out those widely prevalent forms, which give to each group its peculiarly distinctive stamp. Thus no mention is made of deposits of a semi-organic character, such as beds of Oyster shells, which occur in the Littoral zone; nor of the rare mechanical and still rarer chemical deposits in the Oceanic area; because cases like these are of the nature of local and subordinate accidents, which do not from a broad point of view affect the prevailing character of any one of the groups. It is the latter, and not mere accidental accompaniments, that we look to, when we want to find out the circumstances under which any given mass of rocks were formed.

Importance of learning the Conditions under which Rocks were formed.—The great value of a classification like that just attempted, as compared with an arrangement of rocks depending on mineral composition alone, is this; it speaks to us of matters of far greater import than chemical and mineralogical constitution, for it asserts that rocks have not always existed as we see them now, and it assigns to each kind of rock the cause and conditions of its formation. And it is not till we have got to this point, that we realise what the real aim and end of all geological work is; that it is not merely to tell us what rocks are like, but to enable us, when we look at a rock, to say how and where it was formed.

When we can do this Geology becomes, not a mere catalogue of dry descriptions, but a history; and we learn to look upon rocks as the pages of a volume, on which is written an account of what was going on while they were being formed. The student, who knows no more of Geology than he has picked up from the preceding pages, will have begun to realise that every rock has a story of its own to tell, and furnishes to any one, who can read its tale aright, a record of what was the physical condition of the spot, on which it is found, at the time of its formation. Now in studying the physical condition of the earth at present, we do not confine our attention to any single one of its physical divisions, its land surfaces for instance or its oceans; but we strive to learn all we can, alike about the dry land, the

and say they are derivative, inasmuch as it is denudation that furnishes the soil from which plants draw part of their food.

shallow parts and more profound depths of the ocean, the lakes and inland seas, and in short about every one of the varied features and modifications of its surface. It is the aim of Geology to furnish us with like detailed information about the earth as it was during past ages; and, as the only documents, so to speak, from which we can draw this knowledge, are the rocks that were formed during those times, it is of the first importance we should be able to ascertain under what conditions they were formed; because Terrestrial rocks tell us where the dry land lay, Littoral deposits mark the shore line, Oceanic beds the depths of the sea, and Lacustrine formations give us the site of inland bodies of water. It is only when we have been able to study a contemporaneous suite of all these different forms of rocks, that we can arrive at a knowledge of the physical geography of the earth at any past epoch.

We will therefore give up this chapter to an explanation of the way in which the character of a rock enables us to decide on the conditions under which it was formed; and so to map out the different distributions of land and water which have existed at different periods of the earth's past history.

Teaching of Glacial Formations..—Under each one of the above four main subdivisions we might have specified one or more members formed by the action of ice. Thus among the Oceanic group we do find, though but rarely, boulders dropped from icebergs; in Thalassic, Littoral, Estuarine, and Lacustrine beds Boulder Clays and Glacial Mud are met with; while Till and Moraines are important items in the roll of Terrestrial rocks. But it will be better for our present purpose to look upon ice-formed deposits as constituting a separate glacial class, than to rank them as subordinate members of the classes already mentioned. Our object in the present chapter is to see how far we can make out, from a study of any given rock, what were the physical conditions that prevailed when that rock was formed, at the spot where it occurs. Now there is one fact, which all glacial beds, under whatever conditions they were formed, agree in indicating, viz. the prevalence of intense cold; and this fact is of far greater importance physically than the consideration whether they were terrestrial or subaqueous. While therefore these latter points must not be lost sight of, the most important truth to be gathered from glacial formations is the existence of a severe climate.

These remarks and the description of glacial formations in the last chapter will render it unnecessary to say anything further about them in this chapter.

We will now pass to a consideration of the great leading features which distinguish each of the subdivisions of our table.

A.—MARINE ROCKS.

Littoral Rocks.—The Littoral zone of any marine area consists of two parts, the belt between the limits of high and low tide, and a tract of shallow water beyond. Over the first the tides and breakers are constantly at work grinding down material detached from the cliffs or brought within the range of their action by rivers; the bottom of the second is broken up only occasionally during very severe storms. The loose matters lying on the lower of these belts are occasionally transferred from it to the upper, but it is on the latter that the great manufacture of debris goes on; there the wear of the waves, as they advance and retreat, produces great piles of shingle and accumulations of sand. When these are swept out seawards the finely divided parts travel far before they reach the bottom, but the coarse and heavy materials sink down at once and become heaped up in long banks of shingle and sand ranging generally parallel to the coast line. Such banks will evidently be thickest on the side nearest the shore, and will thin away in a wedge-shaped form seawards. These materials also will be very irregularly stratified, for the currents traversing the shallow water will give rise to the structure already described as current- or false-bedding.

Now among the rocks of the earth's crust we find Conglomerates and coarse Sandstones, which resemble exactly the shore deposits of the present day. In composition they are just the same; they have the same wedge-shaped form, for, though they may be followed for long distances in one direction, we find, when we endeavour to trace them in the direction at right angles to this, that they thin out rapidly and become replaced by beds of finer grain. They also invariably show very excessive current-bedding.

Rocks answering to this description then give us the position of an old coast-line, and we know that the side on which they are thickest was the landward side, and that the direction in which they thin out, led to sea.

The rough usage which the materials of such rocks have undergone, has very frequently prevented any remains of animal life being preserved in them, and they are generally barren of fossils. When they do contain organic remains, these consist of the hard parts of creatures that lived in shallow water, such as molluscs, whose shells in such situations grow thick and hard to enable them to resist the pounding of the shingle. They are also liable to enclose the bones of terrestrial animals and land plants, which have been brought down by rivers and have sunk to the bottom near their mouths.

The deposits just mentioned are the most important and characteristic of the Littoral group, but others of a somewhat different nature are formed between tidal limits. In the hollows between shingle- and sand-banks mud and fine sand accumulate, and, when the whole becomes compacted into rock, give rise to lenticular masses of Shale and laminated Sandstone, such as often occur in the middle of bodies of Conglomerate. The surfaces of these finer beds are ripple-marked by the motion of the waves, and stamped with the tracks and burrows of marine animals and the footprints of birds; when they are laid dry by the retreating tide, they are cracked by the sun; sometimes too evaporation of pools of sea water causes the deposition of Crystals of Salt, and these crystals, being afterwards dissolved, leave a cast, which is filled up by sediment, and so models in sand or mud are formed, known as Pseudomorphs.* All these appearances are common in the corresponding rocks, and, where they are met with, indicate a Littoral origin.

Thalassic Rocks.—As we leave the shallow belt which usually fringes a sea-coast and advance into deeper water, the deposits laid down on the sea-bottom become gradually finer in grain, the sandy element, so conspicuous in the Littoral zone, ceases to predominate, and clayey mud replaces it in part: here too mixtures of mechanical sediment with the calcareous remains of marine animals are formed.

Such deposits give rise to finely grained Sandstones, argillaceous Sandstones, Clays, Shales, Mudstones, and impure Limestones.

These deep-water marine beds will show more regularity in their bedding than those of the Littoral zone, because the currents, to which confused bedding is due, become feebler as the water deepens: they will also spread over larger areas and be more uniform in composition, because the finely divided matter, out of which they are formed, remains for a long time suspended in the water and is spread over broad spaces before it sinks to the bottom. The area over which finely divided sediment suspended in river water is distributed, is increased by the smaller specific gravity of fresh than salt water. From this cause the discharge from a river floats on the top of the sea in some cases for hundreds of miles before it becomes fairly mixed up with the salt water, and of course carries along with it its burden of suspended matter.

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* Quart. Journ. Geol. Soc., ix. 5, 187, xxiv. 546: and p. 28.

The quietness of deposition of these beds is favourable to the preservation of the remains of animals, which live in the water where they are formed; hence they will be often highly fossiliferous, but these fossils will be almost exclusively marine, and it will be only very rarely that the remains of land animals or plants will have been carried out far enough to sea to have been embedded in them.

Limestones are by no means rare among the present class of rocks, but they differ from the typical Limestones of the Oceanic area in being very impure, because they are only partly made up of the calcareous portions of marine animals and contain besides mixtures of muddy or sandy sediment. It seems however possible that where rivers very largely charged with Carbonate of Lime flow into the sea, chemical precipitation may take place and give rise to beds of purer Limestone: but it is probable that such cases are very exceptional.[*]

Normal Oceanic Rocks.—In every large ocean there are bounds past which no sediment however finely divided is carried, and beyond these no mechanical deposit can consequently be formed. In the clear pure water of these regions animals flourish, which cannot exist in water fouled by sediment, and by these we saw in the last chapter masses of pure Limestone are built up.

Many such Limestones occur among the rocks of the earth's crust, about whose origin there can be no doubt, because we can still see that they are almost entirely made up of the hard parts of marine animals; other large masses of pure Limestone there are which now show little or no trace of fossils; but to these too we assign an organic origin, because we know of no other way in which they can have been formed, and we suppose that changes, which will be more fully treated of by-and-by, have removed all traces of the fossils which they once contained.

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[*] See Lyell, Principles of Geology, 10th ed., i. 429—431.

In all cases then we look upon great masses of pure Limestone as having been formed by animal agency, and as marking the sites of what were, at the time of their formation, Oceanic areas far remote from land.

In Limestones of this character we almost always meet with siliceous nodules, as for instance Flints in Chalk, Chert nodules in the Carboniferous Limestone of England. The origin of these has been already explained, but it is desirable to recall attention to the almost invariable association of the two kinds of rock, because it is a fact in favour of the organic origin of the Limestone. We know that sea water holds in solution Silica as well as Carbonate of Lime, and that, besides the animals and plants which secrete the latter, there are others living side by side with them, which extract the former; the intermixture of siliceous and calcareous organisms readily explains the presence of Silica in the middle of an eminently calcareous deposit, a fact which it is not easy to account for in any other way.

We must now include in the roll of Oceanic formations deposits like the Red Mud of the Atlantic described in the last chapter, and the rocks which may have been formed in the same way.

We find now and then exceptions to the sweeping statement that Oceanic deposits are mainly of organic origin; these are not numerous enough to upset its general truth, but still require notice.

Erratics in Oceanic Deposits.—Occasionally travelled boulders of large size are met with in the heart of great masses of strata that were formed in still water far away from any land. There are several possible means by which these wanderers may have been carried to their present position.

Large stones often get entangled among the roots of trees, and, when the latter fall into rivers, are floated down the stream and out to sea, till the decay of the wood drops them to the bottom. Another means of carriage is furnished by seaweeds, which sometimes grow to a size large enough to float the rocky fragments to which they attach themselves. Lastly, floating ice is another transporting agent, and in all probability the one which has in most cases been employed. Where the fragments are angular they may have formed originally part of the morainic rubbish on the back of a glacier or ice-sheet, and were borne away on icebergs; where they are rounded, they must have been picked up from the shingle of the beach by coast-ice. The reader will find a description of erratics embedded in chalk, and a discussion of the way in which they may have been brought, in a paper by Mr. Goodwin Austen in the Quart. Journ. Geol. Soc. xiv. 252.

Chemical Deposits in Oceanic Areas.—Under certain circumstances too chemical deposits are formed even in the centre of wide Oceanic areas. Thus Dana ("Coral Islands," p. 294) gives the following section of the deposits, which fill up the lagoon of an old raised atoll, Jarvis Island, situated in lat. 0° 22′ S, long. 159° 58′ W :—

3. Guano.
2. Sulphate of Lime, some compact and crystalline, some soft and amorphous, often two feet thick.
1. Fine Coral debris and shells.

Here the source of the Sulphate of Lime must have been the sea water, which holds small quantities of that substance in solution: when the lagoon became closed, evaporation would concentrate the solution till the dissolved salts were precipitated; if a fresh supply of water were then admitted to the same treatment, and the process repeated often enough, any thickness of Gypsum might be accumulated. Dana further mentions, that, as far as his observations extend, all elevated lagoons have similar deposits of Gypsum, and that Rock Salt frequently accompanies them (*op. cit.*, pp. 182, 297). Imperfect Dolomite is also formed under similar circumstances. Thus the Coral Limestone of the island of Matea contains* a large percentage of Carbonate of Magnesia. This salt does enter into the composition of certain Corals,† but hardly in sufficient quantity to make it possible that they could be the sole source of a rock like this. The Limestone was probably formed out of Coral debris in the drying-up

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* Analysis, Silliman's Journ., 2nd series, xiv. 82 :—

Carbonate of Lime . . .	61·93
Carbonate of Magnesia .	38·07
Specific Gravity . . .	2·690
Hardness	4·25

Some specimens gave only 5·29 per cent. of Carbonate of Magnesia.

† Forchhammer found 2·1 per cent. of Magnesia in Corallium rubrum, and 6·36 in Isis hippuris. (Dana, Coral Islands, p. 99.)

lagoon of an old atoll, which had been converted by evaporation into a strongly concentrated solution of Magnesian Salts (*op. cit.* p. 357).

Attention has been called to these abnormal forms of Oceanic deposit, because we shall see shortly that Rock Salt, Gypsum, Dolomite, and other chemically formed rocks are particularly characteristic of formations originating in inland seas. The cases quoted show, that we must not jump too hastily to the conclusion, that, wherever these kinds of rock occur, the beds among which they are found are necessarily Lacustrine. If, when we look at their surroundings, we find them to be merely subordinate patches in the middle of a great mass of rocks evidently of Oceanic origin, we must decide on the conditions under which the group was deposited from the broad general character of the whole, and not from a few local accidents.

B.—Estuarine Rocks.

Everywhere along the coast materials for the formation of submarine rocks are furnished out of the detrital matter brought down by streams or yielded by the destruction of the cliffs. But, where a large river enters the sea, an unusual amount of sediment is brought in at a single spot, and the accumulations round its mouth tend in consequence to become specially conspicuous.

The distribution of the matters carried down by a great river will depend on the following circumstances: if powerful currents sweep across its mouth, they may bear away the whole or the greater part of the detritus, and little or no deposition may go on opposite the mouth; but if the sea be free from currents, or if the volume or character of the suspended matter be such as the existing currents are unable to remove, deposition will take place as soon as the river enters the sea, the latter will be gradually filled up, and a tongue of land, constantly growing in size, will be pushed out into the marine area.

The projections of land formed in this way are known as Deltas.

Tides both hinder and promote the growth of Deltas. The scour of the ebb tends to sweep away sediment already deposited; while the pounding back of the river during high tide promotes deposition.

Space will not allow of our giving any lengthy description of existing deltas,* but it is desirable that the student should realise the enormous size to which they grow. The fluviatile deposits which form the delta of the Mississippi extend over an area of 12,300 miles, equal to nearly half that of Ireland, and have been proved by boring to be at one spot more than 600 feet in thickness. The delta of the Ganges is not far from twice as large.

The nature of the materials of which deltas consist will vary according to circumstances. Where mountains rise abruptly from the coast, the streams that flow down their flanks will have fall enough to enable them to bring down coarse detritus, and deposits of sand and shingle will be formed around their mouths. But where, as is the case with most large rivers, a broad tract of flat country intervenes between the sea and the mountains on which the sources of the stream lie, the river ceases to be able to carry forward coarse matter as soon as it reaches the low country, and only finely divided sediment reaches the sea. Still, even in the latter case, we may expect alternations of beds of different degrees of coarseness corresponding to the seasons when the river is low, and when it is in flood.

In the arrangement of their materials the deposits of deltas will bear some resemblance to those of the Littoral zone among marine beds. There will be the same current-bedding, the same interlacing of wedge-shaped masses of beds of different mineral composition, and generally the same prevailing irregularity when the whole is looked at on a large scale. We shall also find the surfaces of the beds ripple-marked, rain-pitted, sun-cracked, crossed by animal tracks, and dotted over with pseudomorphs of salt crystals. When the surface of a delta has been raised nearly up to the sea level, the deposits often assume a very complex character; sand-dunes or shingle-banks are piled up, and by damming back the river water give rise to lagoons, in which fresh-water animals live and become embedded; after a while the sea bursts through the barrier and brings with it brackish forms whose remains are preserved in the next series of strata: sometimes the water at one end of a lagoon is salt enough to support brackish-water creatures and sufficiently freshened by the influx of river water at the other end to allow of fresh-water animals living in it, and thus the beds laid down in it show a gradual passage from one form to the other.

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* For information on this head see Lyell's Principles of Geology, 10th ed., i. chaps. xviii. and xix.; De la Beche, Geological Observer, pp. 72, 98; Carl Vogt, Lehrbuch der Geologie, ii. 114.

In some cases deposits of Rock Salt, Gypsum, and other chemical precipitates are formed by the evaporation of bodies of salt water shut off in lagoons.

Occasionally the shutting out of the sea by temporary barriers gives rise to tracts of comparatively dry land, on which marsh-loving plants flourish, and in which land animals that venture on them are liable to get mired, and thus there are produced interstratified terrestrial formations with the remains of the plants that grew on them and the beasts that frequented them. In this way delta deposits show constant alternations of fresh-water, brackish, chemical, and terrestrial formations.

This complexity will be vastly increased, if, while the deposition of the delta is going on, there are changes in the relative level of the land and sea. Suppose the sea-bottom to be sinking slowly, and that the downward movement is interrupted by occasional pauses. During one of the latter the water may be so far filled up that a land surface is produced; when depression begins again, the terrestrial accumulations become covered up by subaqueous deposits, and in this way any number of alternations of the two forms of rock may be produced. This is the character of the fluviatile deposits on which Venice stands: they have been bored through to a depth of 400 feet, and at four different levels beds of turf precisely similar to those now forming on the margin of the Adriatic were met with.

Alternate elevation and depression of the land will lead to the same admixture of terrestrial and subaqueous deposits.

Shape in section of Deltas.—If we could make a longitudinal section along the whole length of a delta, we should find the thickness of the deposit increasing for some distance from the mouth of the river, then beginning to decrease, and at last wedging away to nothing.

Fossils of Estuarine Beds.—The fossil remains preserved in estuarine beds will show a mixture very characteristic of this class of deposits. There will be no deep sea forms, but the shells and fish that inhabit brackish water will be present; with these drifted specimens of fresh-water and land plants and shells, and bones of terrestrial and amphibious animals will occur; occasionally we shall come upon beds enclosing only a fresh-water fauna, and others which are evidently land growths.

We also meet with the shells of Estuarine or Marine mollusca, which are stunted and deformed, as if the conditions under which they lived were unfavourable to healthy growth. These abnormal forms were caused by some sudden increase in the volume of the river, whereby an area, which had for a time been occupied by salt water, became freshened, not sufficiently to kill off the marine inhabitants, but enough to make their surroundings unsuitable to their habits.

Deposits formed by the Union of Deltas.—The deposits then of the delta of a single river will form a very complicated group, and when, in the course of their growth, the deltas of several neighbouring streams come to be united, we get a mass of strata showing still greater irregularity: the sediment brought down by the several rivers may vary very much in character, the prevailing constituent of the detritus of one may be mud, of another sand, and the waters of a third may be so charged with Carbonate of Lime as to promote the abundant growth of calcareous organisms and give rise to beds of Limestone; and in this way, when the united deposits come to form one great rock mass, we shall find in it beds which at one spot are Sandstone, at another Shale, and at a third Limestone, the three forms passing horizontally into one another by gradual steps.

Example of an Estuarine Group.—Among the rocks of the earth's crust we find great groups of strata which show all the peculiarities just described as characteristic of delta deposits: a very good instance is furnished by what are known as the Wealden Rocks of Kent and Sussex. This formation consists of Clays, Sands, Sandstones, Calcareous Grits and impure Limestones: it contains the remains of estuarine and fresh-water shells and crustaceans and fish, which are alone sufficient to decide its estuarine character. We learn further that it was deposited not far from land, because we find embedded in it land plants, insects, the bones of birds, and of terrestrial and amphibious animals, specially a gigantic terrestrial lizard known as the Iguanodon, the footprints of which still remain imprinted on the surfaces of some of the beds. We have therefore all the signs by which we recognise a formation of Estuarine origin, and we can determine also the quarter from which the river that deposited it flowed, and whereabouts the sea lay into which that river discharged itself.

The thickness of the whole mass of strata in Sussex is at least 1,300 feet; as we trace them westwards along the English coast they fall off rapidly, till, at the last spot where they are exposed, they are less than 200 feet thick. Again the corresponding beds on the opposite coast of France show a still more striking decrease in thickness in the direction of Boulogne. The spot where the beds are thickest was evidently in the middle of the estuary; the fact that they thin away both to the east and the west, shows that the water shallowed in those directions, or, in other words, that the margins of the estuary lay towards those quarters. The estuary, therefore, in which these beds were deposited, stretched across Sussex, and its shores lay to the east and west of that county,—that is, its general direction ran north and south. That the sources of the river were to the north, and that the ocean into which it discharged itself lay to the south, we learn from the following considerations. If we cross the channel and examine the corresponding rocks in France, we find the group to consist there of alternations of beds decidedly estuarine with others undoubtedly marine, of the class we have called Thalassic; as we go towards the south-east, the estuarine portions become fewer and thinner till they at last disappear altogether, and at the same time the marine beds gradually lose the Thalassic type and pass into Oceanic Limestones. We have therefore a gradual and complete passage from beds formed at the mouth of a river, through alternations of Estuarine and Marine strata, into rocks formed in an open ocean.

These broad facts show that land lay to the north and open sea to the south-east; and by the aid of more detailed observations, which need not be given here, we can restore to a very close degree of approximation the physical geography of the country at the time this group was being formed. To the north lay a tract of land covered with vegetation and inhabited by the Iguanodon and other creatures: one of the rivers draining this continent discharged itself through a long narrow estuary, which ran in a south-easterly direction across the south-east of England towards the centre of France and opened out there into a broad ocean. The position of this estuary is marked out by the great mass of beds, almost entirely of fresh water origin from top to bottom, in the south-east of England;

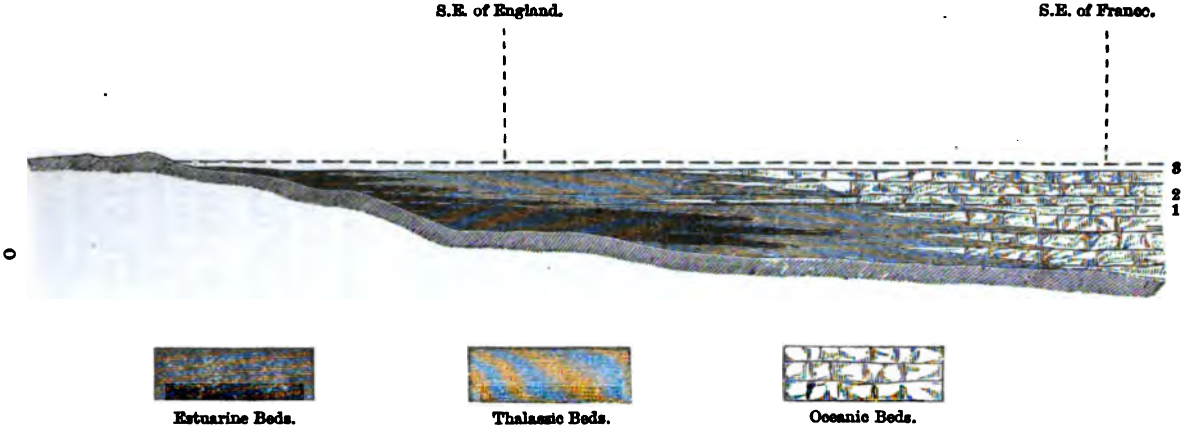

Fig. 33.—Diagram showing the Estuarine Beds of the Weald and their Marine Equivalents.

1. Level to which the sea had risen by the end of the Wealden period. 2. Average sea level during deposition of the Punfield beds.
3. Level to which the sea had risen by the end of the Lower Greensand period.

where we find in France marine beds begin to come in, we know that we have passed the mouth of the estuary and are getting out to sea; and when we find these Marine beds gradually losing their Thalassic character and putting on an Oceanic type, we know that we are well in the marine area.

One more point calls for notice, the character of the Wealden beds, even where they are thickest, proves that they have been deposited in not very deep water. The only way in which this could happen was by a gradual sinking of the land during the period of their deposition. We have independent evidence that such a sinking did take place. Immediately above the Wealden beds there lies a thin group of strata known as the Punfield Formation, which consists of alternations of fresh-water and Littoral Marine strata: during the formation of these rocks then the sea must have from time to time encroached on the area formerly occupied by fresh water. Above these Punfield beds are others known as the Lower Greensand, which are purely marine; and from this we learn, that, by the time these last came to be formed, the sea had permanently overflowed the country. The evidence therefore all conspires to show, that, during the formation of all the rocks we have been reviewing, the land was going down: that during the Wealden period the sea was seldom, if ever, brought over the south-east of England; that during Punfield times it advanced over part of that district and receded; and finally that the country was completely submerged during the deposition of the Lower Greensand.

The relations of the rocks just described to one another have been thrown into the form of a diagram in Fig. 33.

C.—LACUSTRINE ROCKS.

The deposits formed in fresh-water lakes and those of inland seas have some points in common, which may be considered before we come to the characters which are peculiar to each.

The sediment brought into a lake is usually supplied by several rivers, which enter it at different points, which may run over rocks of very different character, and may vary much in their transporting powers. From this cause Lacustrine deposits will show both in a horizontal and vertical direction very marked and often very sudden changes of character. The coarser matter will be thrown down in deltas at the mouth of each stream, and thus fan-shaped masses of Conglomerate will accumulate every here and there along the edge of the water. When we have to deal with a mass of Lacustrine beds, we may, by noting the position of these deltas, fix the boundaries of the sheet of water in which it was accumulated. The more finely divided materials will travel further, and will to a certain extent get mixed together, before they reach the bottom, and thus the central parts of the deposit will be more uniform in character; but even here there may well be numerous alternations of beds differing in colour, composition, and texture, for it is probable that all the inflowing streams will not be at their fullest at the same time, and the one which has the greatest volume and velocity will bring in and spread further its own peculiar sediment, and give rise to a layer, which will partake more largely of the character of the sediment of that stream than of the others. When the turn of the next stream comes, it will lay on the top of this a stratum, in which the distinctive character of the sediment which it brings down will prevail, and so on. Many Lacustrine formations do show numerous alternations of their beds of different characters, and it is probable that it is for the reason just given. Also we must bear in mind, that the streams cannot carry even fine sediment beyond a certain distance from their mouths, and hence the beds will not spread each of them over the whole of the bottom, but will dovetail into one another in a wedge-shaped fashion. The peculiarities just described are well exemplified in the Lacustrine deposits of Auvergne, which the reader will find described in Lyell's "Manual of Geology" (6th ed.), p. 220.

When the water of a lake is low, the surfaces of the deposits forming in it are sometimes laid dry, and then become impressed with rain-pittings, sun-cracks, and other such markings, which we have already seen are produced in other deposits under similar circumstances.

When the streams which feed a lake are small, each will be able to bring down only a small quantity of sediment; and, if this is finely divided, it will be spread over a large area, and give rise to a layer or stratum of small thickness. A change in the character of the detritus will lay upon the top of this a stratum equally thin, but of different composition. Thus the deposit will be subdivided into a large number of very thin beds, and will contrast strongly with the more thickly-bedded and uniform accumulations of a Thalassic or Oceanic area. Fig. 6 gives an instance of this. In the upper fifteen feet there are no less than nine alternations of rock, each occurring in thin layers, which in some cases are further subdivided into laminæ of excessive tenuity; this portion of the section is of Lacustrine or Estuarine origin. The lower twenty-three feet, which consists of Marine rocks, shows only four subdivisions, more massive and blocky in their structure.

Fresh-water Lacustrine Deposits.—Such being the general character of all Lacustrine formations, we must next consider what are the peculiarities which enable us to distinguish those deposited in fresh-water lakes. All Lacustrine beds resemble those of Estuarine origin in many respects, they show the same general irregularity both in the composition and arrangement of the deposit, give the same proofs that the surfaces of the beds have been occasionally exposed to the air, and contain the remains of fresh-water and terrestrial plants and animals. But there is this difference between the two: Estuarine formations usually contain beds with brackish water or marine shells interstratified with those in which fluviatile forms alone occur, or beds yielding a mixture of marine and fresh-water forms; such are of course absent from the deposits of a lake to which the sea never gains access. But in many cases the sheets of fresh water, in which Lacustrine formations have been laid down, have been from time to time invaded by the sea, and the result has been just such alternations of fresh and salt water deposits as we meet with among Estuarine beds. In a case like this, if only fragments of the deposit have been preserved, it will be impossible to say to which class they should be referred: but if the formation has come down in anything like an entire condition, the following considerations enable us to decide this point. Estuarine formations will pass in a certain direction into those of a purely marine origin; we found this to be the case for instance with the Wealden Rocks of England. In deposits formed in bodies of fresh water, though there may be marine intercalations, we shall never observe the formation as a whole to pass laterally into one entirely marine. Further if a Lacustrine deposit be entire, we shall find all round its edges a ring of shore formations, Conglomerates, and similar coarse rocks, among which the deltas of the inflowing streams will be specially conspicuous: in a delta the similar rocks will tend to be crowded round one spot, viz. the river's mouth. In the one case the directions in which the deposits tend to become finer in grain will converge *towards a centre*, the middle of the lake; in the other they will spread out like a fan *from a centre*, the mouth of the river.

A purely fresh-water formation will contain only fresh-water fossils, but there are every now and then exceptions even to this rule. For instance, marine crustaceans* have been dredged up from the depths of the large American lakes, and their remains may well get mixed up with those of fresh-water creatures in the deposits now forming beneath those bodies of water.

Besides the ordinary types of mechanical deposits the following kinds of rock are worth notice as often occurring in Lacustrine beds. Chemical precipitates of Carbonate of Lime and Silica may be formed when springs largely charged with these substances burst out on the banks or beneath the waters of the lake, but the amount held in solution must be considerable in order to produce precipitation; this is often the case in districts where volcanoes either are or have been active. Semi-organic formations also occur, such as the Shell Marls of some small lakes in Scotland, which have been filled up by the deposition of sediment; these beds are described by Lyell as consisting almost entirely of the shells of fresh-water testacea decomposed into a pulverulent marl. Some lakes swarm with Diatoms, the siliceous cases of which accumulate on the bottom and give rise to the deposits of Tripoli or polishing stone: in other cases Diatoms extract iron from the water and cause the formation of Iron ores.

The Lacustrine deposits of Auvergne furnish a good instance of a purely fresh-water deposit; while the Molasse of Switzerland, of which the reader will find a full description in Lyell's "Elements of Geology," chap. xv., is a fine example of a formation in the main of fresh-water origin but containing marine intercalations. There are also very extensive Lacustrine formations in the western states of North America.†

Salt-water Lacustrine Rocks.—The one conspicuous feature which characterises deposits formed in inland bodies of salt water is the presence of great masses of chemical precipitates, such as Rock Salt. Gypsum, and Dolomite.

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* These lakes were probably originally bodies of salt water cut off from the ocean by the upheaval of barriers of land, and have since been freshened by the water poured into them by rivers. Some few marine creatures have been able to accommodate themselves to the change and linger on in their deepest parts.

† See Sun Pictures of the Rocky Mountains, by Prof. F. N. Hayden, chap. vii., and the Reports of the U. S. Geological Survey of the Territories.

It is a significant fact that these forms of chemical deposit are in very many cases associated together, and that the beds in which they occur are either altogether barren of fossils, or contain only the remains of land plants and of terrestrial or amphibious animals, or, if there are any marine forms in them, these are few in number and have a dwarfed and unhealthy look. At the same time those rocks, which are proved by the presence of an abundance of well-developed marine fossils to have been formed in the sea, rarely contain in any quantity the salts which sea water holds in solution. The meaning of these facts has been already hinted at. It is extremely improbable that an open ocean can ever become sufficiently saturated with matter in solution to allow of precipitation taking place; while on the other hand this is the result that must happen in closed bodies of water, and may happen in those which have an outlet if the evaporation be excessive.

We shall better realise the much higher state of concentration that obtains in closed bodies of water than in open sea, by contrasting the two following analyses of the waters of the Mediterranean and Dead Sea:—*

	Mediterranean.	Dead Sea.
Chloride of Sodium . . .	2·9460	12·110
Chloride of Magnesium . .	0·3223	7·822
Chloride of Calcium . . .		2·455
Chloride of Potash . . .	0·0505	1·217
Sulphate of Lime . . .	0·1357	0·452
Sulphate of Magnesium . .	0·2480	
Bromide of Sodium . . .	0·0558	
Carbonate of Lime . . .	0·0113	
Carbonate of Magnesia . .		
Peroxide of Iron . . .	0·0004	
Total solid contents . .	3·7698	24·056

On this head Mr. Sorby has some very pertinent remarks. He states "that some very solid Dolomites contain even now about one-fifth per cent. of salts soluble in water, Chlorides of Sodium, Magnesium, Potassium, and Calcium, and Sulphate of Lime, which are doubtless retained in minute 'fluid cavities.' These must have been produced at the same time as the Dolomite, and caught up some of the solution then present, which is thus indicated to have been of a briny character." But he also states that some Dolomites yet show traces of fragments of organic bodies, and would appear to be made up, in part if not wholly, of comminuted and decayed calcareous organisms, and to have been subsequently altered into Dolomite, possibly by the infiltration of Magnesian Salts of sea water, when it had been so far concentrated that Rock Salt was deposited.* In the latter case we may suppose that the water was for a time sufficiently free from dissolved matters to allow of the existence of animal life and the growth of organic Limestone, and that afterwards the area was flooded by a concentrated solution which transformed the Limestone into Dolomite by percolating through it. Or it may be that some hardy creatures managed to struggle on in the concentrated solution and their remains were buried in the precipitates. We shall have more to say about Dolomites produced by the alteration of Limestone in the chapter on "Metamorphism."

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* Ramsay, Nature, vii. 313. In connection with this subject the student should also consult the papers of this author, Quart. Journ. Geol. Soc., xxvii. 189 241.

The peculiar character of the fossils found in chemically formed rocks is also easily explained. Water highly charged with the salts required for the formation of such rocks is very unsuitable for the maintenance of animal life, and any creatures that manage to exist in it will be stunted in their growth and deformed in shape by the trying conditions under which they are placed.

On these general grounds then we may fairly look upon rocks possessing the characters just described as marking the site of old inland seas, which may have been originally fresh-water lakes that grew salt because they had no outlet, or may have been portions of the sea that had their connection with the main ocean severed by the upheaval of a barrier of land. The latter explanation must be adopted when the fossils are marine.

Red Colour of Inland Sea Deposits.—The rocks, in which chemically formed deposits occur, are in a very large majority of cases of a red tint; and, when they are minutely examined, it is found that they are not red all through, but that the colour is owing to a thin coating of anhydrous Peroxide of Iron which covers each grain, so that, if we looked at a thin transparent section with a microscope, we should see a number of particles red outside and some other colour inside. It is clear from this that Peroxide of Iron must have been present in large quantity in the water in which these rocks were deposited.

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* Report of British Assoc., 1856, Transactions of Sections, p. 77.

And there is nothing surprising in this. There is scarcely a rock in which Iron is not present under some form or other, and many rocks contain it in large quantity; many of its compounds are readily peroxidised by exposure to the air, by the action of water, and by other chemical reactions, and hence all surface streams are liable to carry in suspension Peroxide of Iron. It is highly probable therefore that this substance will be plentifully carried into all lakes; and in the case of closed bodies of water, if it come in in a fine state of division so that it can remain a long time in suspension, it will accumulate and increase in quantity, just in the same way and for the same reason, as the salts held in solution. We can readily understand then why it is that red beds and chemical deposits so very generally go together, and why inland sea deposits are so very generally red.* But it will be hardly safe to go as far as Prof. Ramsay seems inclined to do, and assume conversely that red colour is in itself a proof of inland sea origin. It is a strong presumption that way, but requires confirmation by other tests. There can be no difficulty in understanding how red beds may be formed beneath the sea. The waste produced by the denudation of red rocks will be red, and, when deposited on the sea-bed, will give rise to marine rocks of a red colour. And now that the *Challenger* soundings have made us acquainted with the vast deposits of red clay that are in process of formation beneath the deepest part of the ocean, the idea that all red beds are necessarily of inland sea origin cannot be entertained for a moment. Red beds may therefore be formed under any conditions; and, as the presence of Peroxide of Iron in any quantity generally drives away animals, they will seldom contain fossils enough to enable us to determine whether they are marine or not: it is to the rocks associated with them that we must look if we want to solve this problem.

The surfaces of red beds are often blotched over with blue and green patches, and sometimes blue and green bands are interstratified with them, and the faces of the joints, and the portions of the rock in the immediate neighbourhood of these planes of division, show the same colours. It is probable that the change in hue has been produced by the action of vegetable acids arising from decomposing plants, which rob the red colouring matter of part of its oxygen and convert it into lower states of oxidation. The beds are also sometimes traversed by tubular pipes which may have been formed by the escape of gases generated from the same cause.* The pseudomorphic casts of salt crystals, already mentioned several times, are, as might be expected, very common on the surface of red beds associated with deposits of Rock Salt; we often find other curious warty protuberances, which are sometimes like flattened spheres, sometimes crescent-shaped, and sometimes take less regular forms. These are probably cavities produced by the dissolution of effloresced masses of salt, which were afterwards filled in by mud or sand.†

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* There is a good account of the association of red beds with chemical deposits in the Explication de la Carte Géologique de la France, ii. 90—94. See also Nature, vi. 142, 242.

The red colour of inland sea deposits is one cause of their unfossiliferous character. Peroxide of Iron in water is fatal to the animals living in it: water charged with it coming from mines kills the fish in the rivers, and, if it reaches the sea, the marine creatures fly before it. Sir H. De la Beche has pointed out that the animals, which live on the sea-bed, cannot exist upon a bottom of red mud; but that, if the water above be clear, fishes could swim about in it;‡ and this is the reason why the latter are found fossil in some red beds where the remains of molluscs are scarce or altogether absent. If there were intervals, during which no sediment was brought down, the water might become bright enough to tempt fish into it, and an irruption of red mud might kill and bury them, and so they would be preserved in a perfect state.

Processes by which Chemical Deposits may have been formed.—Considerations such as have been just brought forward certainly lead to the belief that the masses of rock, generally red, with which Rock Salt, Gypsum, and Dolomite are associated, were deposited partly by precipitation from saturated solutions in inland seas. But it is by no means an easy task to trace out all the steps of the process, and to say what were in each case the exact chemical reactions by which the result was brought about.

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* De la Beche, Memoirs of Geological Survey of Great Britain, i. 53; Maw, Quart. Journ. Geol. Soc. of London, xxiv. 351; Dawson, Ibid., v. 25.

† Mr. Binney has noticed these on the surface of beds of Permian Marl, Mem. of Lit. and Phil. Soc. of Manchester, vol. xii.; Geology of the country round Stockport, (Mems. of Geology Survey of England and Wales), p. 36; see also Jahrbuchder k. k. Geol. Reichsanstalt, xxiii. 252.

‡ Memoirs of the Geological Survey of Great Britain, i. 51.

Rock Salt.—For Rock Salt mere evaporation will suffice. In such a case as the Great Salt Lake of Utah, into which rivers run but from which none run out, where the streams flow over a country on the surface of which salt is constantly efflorescing from below, and when the evaporation is greater than the supply, deposition of salt must go on.

Again in cases when an area is periodically inundated by the sea and then left dry, or where portions of sea water are cut off from the main body by temporary barriers, such as shingle-banks, sand-dunes, or the upheaval of a land barrier, evaporation would produce deposits of Salt; and, if the process be repeated often enough and gentle subsidence go on meanwhile, any thickness may be accumulated. One instance of this kind is found in the Runn of Cutch mentioned by Lyell (Elements, 6th ed. p. 446; Principles, 10th ed., vol. ii. p. 98.)* The great deposits of Rock Salt in the Bitter Lakes of the Isthmus of Suez seem also to be a case in point. This bank is estimated to have contained 970,000,000,000 kilograms of salt, its superficial area is about 66,000,000 square metres, and it is composed of layers varying in thickness from 5 to 25 centims. The basin in which this deposit lies seems to have been every now and then filled by inundations from the Red Sea, and during the intervals between two successive incursions evaporation concentrated the solution and threw down a layer of salt.†

There are two other common rocks, which have most probably in many cases been formed by chemical action—Dolomite‡ and Gypsum. It so very frequently happens that these two rocks are found together, that it is likely that in many cases they were produced at the same time and by the same reaction, and that the formation of the one was necessarily accompanied by the production of the other. In other cases we meet with large masses of Dolomite which are not accompanied by Gypsum, and Gypsum not associated with Dolomite.

Various attempts have been made to imitate experimentally the processes by which Dolomite may be supposed to have been produced by precipitation from a solution of Salts of Lime and Magnesia; but the effects of chemists in this direction have not as yet been particularly successful. Several of the proposed reactions are clearly inadmissible, because, though the experimenters have succeeded in throwing down either Dolomite or a mixture of the Carbonates of Lime and Magnesia, they were obliged to employ temperatures and pressures far greater than we are at liberty to suppose prevailed during the formation of actual Dolomite.*

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* Also Sir Bartle Frere, British Association Reports, 1869, Transact. Sections, p. 163.

† Comptes Rendus, June 22, 1874.

‡ For shortness I use this term here to include not only true Dolomite, but Dolomitic and Magnesian Limestones as well.

Among the methods which naturally suggest themselves as likely to have produced Dolomite, the one that first occurs to the mind is precipitation from the waters of mineral springs. Cases where Magnesian Limestones and possibly Dolomite Limestones have been thus formed are known; † but it is not certain that Dolomite can be formed directly in this way. Bischof's experiments rather tended to show that this was not likely. When he attempted to precipitate Carbonate of Lime and Carbonate of Magnesia together by evaporation from a solution in water, he found that the first salt, because it was the least soluble, was at first thrown down almost exclusively; then a mixture of the two salts was precipitated, and then Carbonate of Magnesia alone; and he thought a deposit produced in this way would consist of Limestone at the bottom, possibly a little Dolomite in the middle, and Carbonate of Magnesia at the top.‡ It is worthy of notice, however, that he speaks of the strong "tendency to the formation of double salts which characterises magnesia;" and it is possible, that even supposing the two carbonates to be precipitated separately, this tendency might lead them afterwards to rearrange themselves and form Bitter Spar. In connection with this part of the subject, an observation of Sterry Hunt's also seems important. In repeating an experiment of Marignac's, he found that Carbonate of Magnesia is quite ready *at the moment of its formation* to unite with Carbonate of Lime into Dolomite; but when he substituted Magnesite for newly formed Carbonate of Magnesia, he found that it showed no such aptitude to combine with the Carbonate of Lime.* It would, therefore, seem to make all the difference in the world in this case, whether the Carbonate of Magnesia is in its ordinary condition, or whether it is newly set free from combination or newly formed; in the first case there will be no tendency to form Dolomite with any Carbonate of Lime that may be present, in the second the union with Dolomite may take place.

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* Under this head we may reckon the explanations proposed by *Forchhammer*, Ann. de Chem. et Phys. xxiii.; *A. Favre* and *Marignac*, Leonhard's Jahrbuch, 1849, p. 472, Bull. Soc. Géol. de France, 2nd ser. vi. 318; *Haidinger*, Poggend. Annal. lxxiv. 591; Leonhard's Jahrbuch, 1847, p. 862; *Morlot*, Leonhard's Jahrbuch, 1847, p. 862, Liebig and Kopp, Jahresbericht, 1848, ii. 600. Some of the above references are second-hand, and I have not been able to verify them. See also Bischof's Chemical Geology, iii. chap. 53; Naumann's Geognosie, i. pp. 523, 714; Zirkel, Petrographie, i. 243.

† Liebig and Kopp, Jahresbericht, 1853, p. 929; Leonhard's Jahrbuch, 1838, p. 62, 1840, p. 372; Zirkel, Petrographie, i. 243; Naumann, Geognosie, i. 523, *note*, 714, *note*.

‡ Chemical Geology, iii. 167, 169.

Dr. Sterry Hunt has given special attention to the subject now before us, and he has suggested two reactions, by one of which Dolomite alone, and by the other Dolomite and Gypsum, may be produced by precipitation.†

The first method he suggests is as follows:—When alkaline water containing Bicarbonate of Soda in solution acts upon sea-water, the soluble salts of lime and magnesia contained in the latter are decomposed. The lime salts are first acted upon, and Carbonate of Lime is precipitated accompanied by two or three hundredths of Carbonate of Magnesia. When this has been effected, a solution of Carbonate of Magnesia remains, which on evaporation deposits Hydrated Magnesian Carbonate.

He remarks that the separation of Magnesian Carbonate does not suppose a high degree of concentration, and may have gone on when animal life was present, so that magnesian beds formed in this way may be fossiliferous. Before, however, precipitation could take place, a degree of concentration would probably be arrived at greater than that which animals can bear, and a more or less sudden destruction of the forms of life would occur, giving rise to a deposit abundantly fossiliferous. When the water had been cleared by precipitation, fresh individuals might migrate into it, to be in their turn destroyed and entombed when a state of saturation was again arrived at.

Again Dr. Hunt has suggested the following as a method by which Dolomite and Gypsum may be formed together.

When water containing Carbonate of Lime is mixed with Sulphate of Magnesia, it gives rise by double decomposition to Carbonate of Magnesia and Sulphate of Lime. Dr. Hunt found that, if the solution be concentrated by evaporation, Gypsum is first thrown down, the Carbonate of Magnesia remaining dissolved. If now an additional supply of water holding Carbonate of Lime in solution be furnished, further evaporation may cause the two carbonates to fall down in a state of intermixture,* and thus a precipitate containing the elements of Dolomite will be obtained.

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* Silliman's Journ., 2nd ser. xxviii. 184.

† Silliman's Journ., 2nd ser. xxviii. 170, 365. Report on the Geology of Canada to 1863, p. 575.

It will be noticed while both these reactions give us the elements of Dolomite, neither of them produces directly Dolomite itself. The union of the carbonates into true Dolomite or Dolomitic Limestones, Dr. Hunt thinks, must have been brought about afterwards by the aid of pressure and temperature, but he states that the lowest temperature at which the combination can be effected has not been ascertained. Bearing in mind the tendency towards the formation of double salts which magnesia is stated to exhibit, it seems not impossible that combination may take place slowly by simple chemical affinity without the aid of any very large amount either of pressure or heat.

We cannot say then that the problem of forming Dolomite by direct precipitation has yet been solved. It has not been found possible, under the conditions which we can command, to effect this experimentally; but it by no means follows that such a method of formation is impossible: the ingenuity of chemists has hardly exhausted every possible combination that might lead to such a result; and, even were this the case, it is perfectly possible that the necessary conditions may be such as we cannot imitate in our laboratories. In fact, imperfect as has been at present the success of experimenters, they have got quite far enough to justify the belief that the process consisted in some reaction between calcareous and magnesian salts in solution. What those salts were, and what was the exact nature of the reaction, have yet to be learned.

There are other Dolomitic and Magnesian Limestones which have been formed by the alteration of ordinary limestone. These will be treated of in the chapter on Metamorphic Rocks.

We have already seen our way in a dim sort of fashion to a method by which Gypsum and Dolomite might be formed together; we have yet to explain the origin of great masses of Gypsum unaccompanied by Dolomite. Several explanations have been offered to account for such deposit by chemical precipitation. It is evident that, if streams holding Sulphate of Lime in solution discharge themselves into a closed body of water, a saturated solution would at length be produced, and the salt would be thrown down. The precipitate might take the form of either of Anhydrite or Gypsum; we do not know the conditions which determine which of the two it will be, but it has been suggested that pressure will decide whether it is hydrated or anhydrous. Again it has been suggested that submarine volcanic outbursts may discharge sulphurous acid, which would be converted into sulphuric acid, and this, acting on the Carbonate of Lime in solution, would give rise to gypsum. Another suggestion is that solutions of alkaline sulphates have been poured into sea-water, and that mutual decomposition has gone on between their contents and the Chloride of Calcium of the sea-water, which has resulted in the formation of Sulphate of Lime and soluble alkaline chlorides.

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* Bischof's experiments, described a little way back, seem against this result.

Whatever explanation is adopted, we must in all cases have closed bodies of water, in order to obtain the saturation necessary to produce precipitation.*

Other Gypsums which are probably the products of alteration of Limestone or Anhydrite will be considered under the head of Metamorphic Rocks.

Sources of the Materials for Chemical Deposits.—We have next to inquire from whence the various substances necessary for the formation of chemical deposits may be supposed to have been derived.

Sea water contains in small quantities the salts which we have enumerated as having possibly given rise to chemically formed rocks. If therefore a portion of the ocean were cut off by the formation of a land barrier and the solution concentrated by evaporation till precipitation ensued, one or more of these rocks might be formed; and if fresh supplies were from time to time introduced by an opening of the barrier, and again shut off by the closing of the opening, or if by inundation or any other means the area was refilled, considerable thicknesses of precipitate might be formed. In many cases however we can scarcely imagine this process to have been repeated often enough to give us the great masses which actually exist. We then turn to inland closed sheets of water into which streams charged with the necessary ingredients discharge themselves. These streams may in many instances derive their dissolved matter from the rocks over or through which they flow. The decomposition of Iron Pyrites will give the Peroxide of Iron necessary to produce the prevalent red colour: Limestone yields Carbonate of Lime, Dolomite that salt and Carbonate of Magnesia, and Gypsum Sulphate of Lime.

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* The student may refer to Bischof, Chemical Geology, i. chap. 19; Naumann, Geognosie, i. 760; Zirkel, Petrographie, i. 268—273.

To the amount of dissolved matter furnished in this way we must add that brought in by mineral springs. These often rise from considerable depths, where the temperature is high and the increased pressure enables the water to hold larger amounts of Carbonic Acid and other solvents than at the surface, and so increases its dissolving power. The most powerfully charged mineral springs occur in volcanic districts, and it is probable that in many cases the materials necessary for the formation of chemical rocks came directly from a volcanic source. In other cases the requisite components may have been furnished by the destruction of previously existing rocks of a similar character; but these latter probably originally drew their ingredients from a volcanic origin, so that it is likely, that in all cases we must look upon volcanic action as the agent, which, either directly or ultimately, furnished the materials for the formation of chemical rocks. We shall again touch on this subject in the next chapter.

Example of Chemically formed Deposits.—As an instance of deposits probably formed, in part at least, by precipitation in an inland sea, we may take the Magnesian Limestone and its associated beds of the north-east of England.

This formation consists of Limestones more or less magnesian, Red Marls and Sandstones, and Gypsum: parts of it are fossiliferous, but the number of species is small, and the individuals are many of them puny and show strange variations from their normal form. On these and other grounds we are led to look upon the group as an inland sea deposit, and, when we come to examine its members separately, we can form some notion of the succession of events that led to their formation. The group shows the following main subdivisions beginning from the top:—

5. Upper Limestone or Brotherton Beds.
4. Red Marls and Sandstones with Gypsum.

3. Small-grained Dolomite.
2. Sandy Magnesian Limestone.
1. Quicksands, and Marls with thin beds of Magnesian Limestone.

The lowest division is mainly of mechanical origin and seems to have been deposited before concentration had gone far enough to produce general precipitation. The quicksands occur in local patches of small extent and show marked current-bedding; they are probably portions of deltas spread out wherever a stream entered the lake; the marls were formed out of muddy sediment further within the area, and the thin bands of impure magnesian limestone that are interbedded with them were probably thrown locally in pools, where the solution became concentrated enough to give rise to precipitation.

The second division is an extremely sandy Magnesian Limestone; the sand must have had a mechanical origin, the dolomitic portion was probably a chemical precipitate. We may therefore suppose that during the formation of this portion precipitation and the deposition of sandy sediment went on together. Some of the beds of this subdivision however show numerous traces of animal remains: these may have been organic limestones formed when the water became for a time clear enough to allow of creatures living in it, and afterwards altered by percolation when the water became saturated with magnesian salts. It is in this division that most of the fossils occur: they have as a rule the character already mentioned, but it is important for our present purpose to note that one mollusc, *Axinus obscurus*, forms an exception to this rule: it occurs of great size and in considerable numbers, and would seem to have been a hardy creature that could stand almost anything and live almost anywhere.

The third division differs from that below it in containing a much smaller admixture of mechanical matter, in parts probably it approaches very nearly to a true Dolomite. During its formation therefore precipitation must have gone on vigorously. Except a few traces in its very lowest beds this limestone contains no fossils, and the meaning of this evidently is that the increasing concentration of the solution, which was the cause of the greater purity of the rock, was too much even for the hardy creatures that had struggled on during the deposition of No. 2, and that all animal life was either killed or driven away.

During the deposition of No. 4 mechanical action predominated, but the beds of Gypsum show that chemical agency was also at work.

The Limestones of the topmost division are in many cases scarcely magnesian at all, and they contain a few sadly stunted fossils. During their formation therefore the water must have been so far free from magnesian salts as to be just habitable. It is curious that the only three species of shells found in this division occur also in No. 2: these we must suppose escaped destruction when the water became unbearable during the formation of No. 3, struggled on in some sheltered nooks or corners, perhaps some way up the rivers, and came back into the lake when matters began to mend a little. As we should expect, among the survivors is the shell which showed so robust a constitution during the formation of No. 2, *Axinus obscurus;* but even this tough fellow had evidently had a hard time of it, for he comes back very much dwarfed in size.

The formation of this group of rocks then may be supposed to have taken place in an inland body of water fed by streams which brought in both mechanical sediment and matter in solution. As time went on the water would become more and more strongly charged with dissolved matter, and accordingly as we ascend from lower to higher beds we find the rocks growing more and more chemical in their character: at the same time all traces of life disappear because the increasing concentration killed or drove away such animals as had managed for a time to struggle on. When, later on, the proportion of obnoxious salts decreased, a few of the animals which had found some sheltered spot where they could live, came back, but they show by their puny size how hard had been the struggle they had gone through in the meanwhile.*

D.—TERRESTRIAL ROCKS.

We do not propose to add anything here to what has been said on the subject of Terrestrial rocks in the last chapter. It is hoped that the descriptions there given will enable the reader to recognise an old land surface, whenever by a happy accident such a relic has been sealed up among rocks and handed down to the present day.

Application to a particular instance.—We will conclude this chapter by an example of the way in which the principles laid down in it enable us to map out the distribution of land and sea that existed, and to determine the changes in physical geography that happened, during a period in the earth's lifetime long past by. The group of rocks known to geologists as the Triassic formation will serve our purpose admirably, they have been traced and identified over a very large part of the world; as we follow them from place to place we find them continually changing in character, and the form they assume at each spot tells us in unmistakeable language what were the physical conditions in that quarter during the time of their formation.

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* For further details respecting these rocks, see Quart. Journ. Geological Society of London, xvii. 287.

In England this formation consists exclusively of Red Sandstones, Shales, and Marls. It contains thick lenticular masses of Rock Salt and Gypsum. No marine fossils have been found in it, but it yields remains of plants and terrestrial reptiles, with fishes and minute crustaceans. Its beds show plentifully ripple-marked and sun-cracked surfaces, with pseudomorphs of salt, and occasionally reptilian footprints. All these characters lead us to look upon the English Triassic rocks as having been formed in inland seas, and to conclude that the area they occupy was part of a broad continental tract diversified by large closed sheets of salt water.

The beds just described pass upwards into a thin band of shale, sandstone, and limestone known as the Penarth beds, which contain some marine fossils. The character of these rocks shows they were formed in shallow water, and their fossils prove that land was not far off, for besides the marine forms they include the remains of terrestrial mammals. The group puts on more and more pronounced littoral characters as it is traced westwards. The Penarth beds pass up insensibly into a more purely marine formation called the Lias. This group of rocks tells us, that after a while the continental area of Triassic times was gently submerged, that the sea stole over it from east to west, not reaching beyond the south-west of England during the formation of the Penarth group, but gradually extending its range as Lias times drew on.

When we come to the Triassic rocks of Central Europe, we find them more complicated than their English representatives. A large part of them are Red Sandstones and Shales containing chemical deposits of Rock Salt, Gypsum, and Dolomite, which seem to have been formed in inland bodies of salt water; but interstratified with these are many beds containing marine fossils; among the most conspicuous of the marine intercalations is a thick mass mainly composed of limestone, called the Muschelkalk. The inference to be drawn from these facts is, that during Triassic times the centre of Europe was in the same condition as England, a continental tract with large salt lakes; but there was this difference between the two cases: in England we have no proof of the presence of the sea, while here we have evidence that the sea was continually making incursions over the land. The longest and most important of these submergences was that during which the Muschelkalk was formed, and by noting the directions in which that group loses its calcareous character and puts on a littoral type, we can determine how far the sea encroached. Above all these rocks comes a band corresponding in every respect to the Penarth beds of our island.

Going still towards the east we find the Triassic beds under yet another form. In the Eastern Alps and Lombardy they consist of thick masses of limestone, swarming with marine fossils, and it is only in their lowest division that they contain any beds likely to be of inland sea origin. Here then there must have existed, during the greater part of the Triassic epoch, an open ocean, in which great masses of organic limestone grew up. It is worthy of note that the fossils found in the marine intercalations of the Trias of Central Europe are also met with in these easterly calcareous equivalents. Above these limestones come the Kössen beds, a group which corresponds to the Penarth beds of England.

Putting all these facts together we arrive at the conclusion, that during Triassic times the physical geography of what is now Europe was as follows. To the east there was a broad open ocean and to the west a continent with large salt lakes, and the limestones of the eastern area were accumulated in the one at the same time that the inland sea deposits of the west were being formed over the other. During the whole of the period there were oscillations of level, in consequence of which the sea from time to time advanced over parts of the land surface and then retreated, but none of these incursions reached as far west as England. Whenever the sea spread itself westwards, it would bring with it out of the eastern ocean those forms of life which were of a migratory turn, and hence the fossils found in the marine intercalations of the centre of Europe are also met with in the limestone of the Eastern Alps: other forms, not so ready at shifting their quarters, are peculiar to the latter. Finally the tendency of the sea to push westwards culminated in a general submergence, which covered the land as far as the south-west of England with a shallow sheet of water in which the Penarth beds were deposited; and a continuation of the depression resulted in producing the still more widely spread Liassic ocean.

CHAPTER VI.

VOLCANIC ROCKS.

"Interdum atram prorumpit ad æthera nubem,
Turbine fumantem piceo et candente favilla;
Interdum scopulos avulsaque viscera montis
Erigit eructans, liquefactaque saxa per auras
Cum gemitu glomerat."

VIRGIL.

SECTION I.—CAUSE OF CRYSTALLINE TEXTURE.

WE may next turn our attention to the second great class of rocks, those namely which are characterised by a crystalline texture.

Origin of Crystalline Rocks.—The first consideration to guide us in our researches into the method of formation of these rocks is the fact that bodies crystallise, when they are precipitated from solution or when they solidify from a state of igneous fusion, provided the process in either case be slow and gradual.

With regard then to the origin of Crystalline rocks we have two hypotheses to try, either they have been precipitated from solution or they have cooled down from a fused condition. The former of these two notions was for some time favoured by geologists; the constituents of these rocks were supposed to have been somehow held in solution in some sort of ocean, and in some way or other to have been precipitated from the dissolving menstruum. Such an hypothesis involved wild and improbable assumptions; but what told against it more strongly was the fact, that a very cursory examination of the Crystalline rocks sufficed to show that many of them possessed sundry striking points of resemblance to those products of igneous fusion, which are poured forth by modern volcanoes or are formed artificially by the action of heat; and the more closely such rocks were studied, the more numerous did these points of resemblance become.

Before going any farther we will take a particular instance, and give a sketch of the line of reasoning, which in that case leads us to believe that a Crystalline rock was formed in the same way as the lava of modern volcanoes.

Let us examine a specimen of Crystalline rock which possesses the texture already described as Vesicular. Its surface is full of bubble-shaped holes, and if we can form any reasonable conjecture as to the manner in which these holes were produced, we shall have made considerable way towards explaining the origin of the rock. It may be that we notice by the roadside a heap of stones, some of which show just the same vesicular structure as our specimen. We ask the stone-breaker where they came from, and learn that they have been brought from a neighbouring iron-works, and are called slag. Inquiring at the works how this slag is produced, we learn that it escapes in a molten state from the furnace and is allowed to cool in the open air, and that the cavities are caused by the boiling up and escape of contained gas. Here then we get a clue, but before we can safely conclude that our specimen was formed in the same way, we must make sure that there is something in Nature's workshop which corresponds to the blast furnace, and is capable of pouring out molten matter similar to that of which our specimen is composed. We find the requisite engine in a volcano; and, on comparing the hardened surface of lava streams with the specimen, we find them to agree not only in being vesicular, but in so many other respects besides, that we have no hesitation in concluding that the rock from which the specimen was taken is an old lava-flow.

On such general grounds then, and on the strength of more detailed considerations to be explained in this chapter, we are quite justified in concluding that a large body of the Crystalline rocks were once in the same semi-fused state as modern lavas, and that they have been formed in the same way and under the same conditions as the lava-sheets that are poured out by active volcanoes. To such we may give the name of *Volcanic* rocks. But there are other Crystalline rocks to whose formation such an explanation will not exactly apply.

One group, of which Granite is the type, while they agree with subaërial lavas in their crystalline texture, differ from them in several essential particulars, the most important of which is that they never show the vesicular and slaggy textures which are universally present in those products of volcanic fusion which have cooled and hardened in the open air; and though there can be no doubt that they and lavas are closely allied, the conditions under which the two were formed must have been widely different.

Another class, equally crystalline, which are usually styled Metamorphic Rocks, can be shown to owe their crystalline texture to the action of heat, but have certainly never been even so fluid as lava.*

These three subdivisions are established on sound grounds, and may be usefully employed, but the bare fact that heat has played an important part in the formation of the rocks of each, raises a suspicion that the difference between them may be after all one of degree and not of kind. It seems not unlikely that a rock may have been in one case rendered crystalline without being melted, and so what we call a Metamorphic rock has been produced; and that in other cases the very same rock has been more intensely heated and melted down into a semi-fused lava. That the process, in a word, which gave rise to Metamorphism, when carried further, has resulted in the production of lava. And further, the many points of resemblance between Volcanic and Granitic rocks suggest the idea that they are both essentially lavas, and that the differences between them are due to the conditions under which they cooled. For we must recollect, that, besides the rocks produced by the ejection of matter by volcanoes into the open air, which we can see, there are others in the course of formation by the same agency underground, which we cannot see: these we can easily realise will differ in compactness and other respects from subaërial products, and it is among these we shall find that we must look for the analogues of the Granitic and other allied rocks. And this leads us to repeat a remark already made, that the inquiry into the origin of Crystalline rocks is by no means so easy as the corresponding investigations in the case of sedimentary deposits. In the latter case the whole process of formation goes on we may say before our eyes, and every step in it can be observed and recorded: but the causes which have given rise to Crystalline rocks have their seat of action below the surface, and we can only infer what is its probable mode of operation there from the partial manifestations of its energy, which take place when it breaks forth into eruption in the open air.

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* Since heat has been concerned in the production of all these rocks, they might all be styled "Igneous;" but this term is usually restricted to the Volcanic and Granitic rocks.

It was desirable to give the reader a hint as early as possible that the three classes of Crystalline rocks just mentioned are in a manner akin to one another; but he must not expect to see clearly all the grounds on which the suggestion is based till he has gone through this and the next two chapters.

In the case of stratified rocks we found that some of them differed in no respect whatever from bedded accumulations now in the course of formation: in other cases, with many points of resemblance between the two, differences do exist, but these differences were shown to be due to the changes which had been wrought in the rock during the long time that had elapsed since its formation, and they therefore in no way shook our belief, that the rock was originally just such as the modern deposit, which it still resembles in many points. Just so many of the rocks now under consideration can be in no respect distinguished from the products of active volcanoes: in other cases, though the resemblance is very close in certain points, the parallel is imperfect in others. We shall see however that even in the case of the latter we are not necessarily driven to conclude that they had other than a volcanic origin, for, just as in the case of sedimentary rocks, alterations since the date of formation may have given rise to the differences.

We shall in this chapter deal mainly with those Crystalline rocks which approach closely the molten products of modern volcanoes. And it will be convenient to consider along with these other rocks, not Crystalline, which are formed wholly or in part of fragmentary matters showered out by volcanoes.

One word of warning, before we go any farther, will be desirable. The reader may have noticed that we have spoken of the imperfect fluidity of lava. It is important that he should realise at the outset that lava is not molten in the same sense as iron when it flows out of a furnace. It is in most cases only partially fused, and owes its power of flowing in large measure to the fact that it is full of steam. Dry heat therefore and heated water both have a share in its formation, and it is to the assistance of the latter that it owes to a great degree its crystalline texture. The formation of crystals by heat alone is distinguished as the "*dry way;*" by water or some liquid, as the "*wet way;*" and when both act together the process is known as "*hydrothermal action.*" It is to the last that the formation of lava is due, and though we may for shortness speak of the fusion of lava or of fused masses of igneous rock, we must always recollect that such expressions are strictly incorrect, and we must never for a moment forget that water as well as heat was always present.*

SECTION II.—PHENOMENA AND PRODUCTS OF VOLCANIC ACTION.

Since we are led to look to volcanic agency for the source of many of the igneous rocks, it will be necessary to study the action and products of modern volcanoes, if we would understand fully how these rocks were formed.

Volcanic eruptions occur sometimes through vents which have previously given exit to similar outbreaks, or they burst forth on spots where they have been hitherto unknown. In either case they are heralded, whenever they are of a severe character, by earthquakes, more or less violent, but confined to the neighbourhood of the vent, and by underground explosions resembling the rolling of musketry or the fire of heavy artillery.

After a while the ground is rent asunder, and fissures or orifices torn through it. From these there rush up with loud explosions bodies of elastic vapour, which rise high into the air in the shape of a column, and spread out, as they condense, horizontally in cloud-like masses.

The elastic fluids carry up with them fragments of the rocks through which they have torn their way, and these falling back are again and again shot up, till they are reduced by continued trituration to dust and powder known as Volcanic Ash. Part of the ejected materials falls back into the vent, part accumulates around the orifice and is piled up round it in a mound, and as layer after layer is added to this heap, a conical-shaped hill is gradually built up, through the middle of which a channel or chimney is kept open by the repeated discharges of vapour.

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* On the share which water has had in the formation of Crystalline rocks, see Delesse "Recherches sur l'origine des Roches" and "Etudes sur le Métamorphisme des Roches." It is impossible to praise too highly the exquisite clearness and extensive research of this author, but now and then he rides his hobby somewhat hard.

After a while a mass of half-molten rock, or lava, which has been all the time boiling up from below, wells up the central chimney, and, on reaching the summit, streams over the edges and down the sides of the cone, forming, as it cools, irregular layers that mantle round it. Over these fresh coatings of ejected ash are heaped, and are in turn covered by other flows of melted rock, either from the top of the chimney or from openings burst through the flanks of the cone.

The violent paroxysms, which accompany the eruption, sometimes rend and tear open fissures in the cone; into these lava is forcibly injected, which on hardening forms ribs of rock known as "dykes."

Producing Causes of Volcanic Eruption.—We can explain only very imperfectly how the phenomena just described are brought about, but thus much is clear. There is beneath the surface a large mass of the intensely heated lava: whether this lava has risen from some deep-seated reservoir of permanently molten matter, or whether a sudden accession of heat has melted down part of the solid crust of the earth, we don't know and do not seem likely to have any means of knowing; all we can say is that the lava is there. Along with it there is water in the state of high-pressure steam, whose tension is continually increasing as the temperature rises. The expansion of the lava and the elastic force of the vapour, in their attempts to force a way through the rocks that hold them back, cause the preliminary earthquakes and underground detonations. At last an outlet is gained, and then with a tremendous burst the imprisoned steam flashes forth in repeated explosions. In the meantime the vapour still retained within the body of the lava forces the latter upwards till it meets with an opening, from which it continues to escape till the pressure is so far abated as to be unable to produce any further flow.

Structure of Single Cone.—The cone produced in the manner just described consists of alternating sheets of ash and lava mantling irregularly over one another, and *all dipping outwards from the centre.* Fig. 34 is a vertical, and Fig. 35 a horizontal section or ground plan, of such a cone. The successive ejections of fragmentary materials or ash are seen to be arranged in irregular layers wrapping over one another, and all dipping outwards from the central axis: interbedded with these are sheets of hardened lava with a similar arrangement: cracks radiating from the centre and filled up with lava form a number of dykes intersecting the cone: lastly in the middle is a pit or chimney, called the crater, filled up with a mass of lava. The vertical section shows the outward dip of the layers;

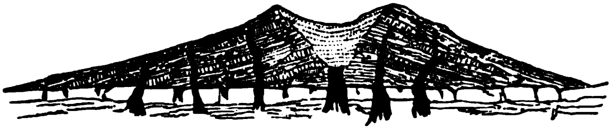

Fig. 34.—Vertical Section of single Volcanic Cone.

while in the horizontal section we see their arrangement in rudely concentric circular sheets round the axis, and the radial disposition of the dykes.

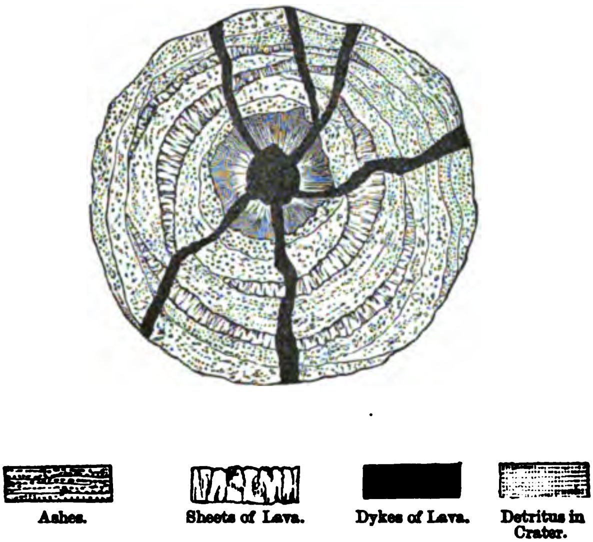

Fig. 35.—Horizontal Section of single Volcanic Cone.

Cessation and Repetition of Eruption.—When the accumulated mass of vapour, which was the cause of the eruption, has discharged itself, a period of repose follows, and will be either permanent or broken by fresh eruptions according to circumstances. If there be no fresh accession of heat beneath, the volcanic action will grow fainter and fainter, till it at last dies away altogether and the volcano becomes exinct. If heat be still supplied, but uniformly and in moderate degree, and if nothing happen to stop up the chimney, the volcano passes into a state of permanent gentle eruption. The chimney however may become choked in many ways. Atmospheric denudation may wash down into it the loose materials of the cone,* or it may become plugged up with hardened lava. Whenever from these or other causes the outlet for heat and its products is closed, vapour and lava again accumulate, and at last another eruption becomes necessary to release them. A repetition of eruption may also be caused, without the vent being closed, by a sudden accession of fresh heat below.

Thus it frequently happens that eruption follows upon eruption, and at each active period the heap of ejected materials is added to, till the original cone grows into a mighty mountain. The outbursts sometimes take place all of them from the same orifice, and then the volcano, whatever its size, consists of only one cone of considerable regularity of outline. But more frequently each fresh eruption gives rise to new vents, in which case the volcanic mountain contains a confused assemblage of cones grouped round a central peak.

Truncation and breaching of Cone: Production of Crater and Cone within it.—As yet we have looked on successive eruptions as continually adding to the mass of the mountain, but such is by no means always the case. When the volcano has attained a certain height, it frequently happens that its sides are not strong enough to support the pressure of the column of lava in the chimney. The melted rock then forces out a way for itself through openings torn in the flanks of the cone, or sometimes breaks down the whole of one side of the mountain. The result is a cone breached by one or more great radial valleys.

The paroxysms too, that accompany the more violent outbursts, often blow away bodily into the air a large part of the cone, and tear open a huge crateral hollow, reaching far down into its heart. And in this way much of the work, which previous eruptions have performed towards

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* In Fig. 34 the interior of the crater has been partly filled up in this way: the detritus is shown by faint dotted lines, and is arranged in layers dipping *inwards* towards the centre of the cone.

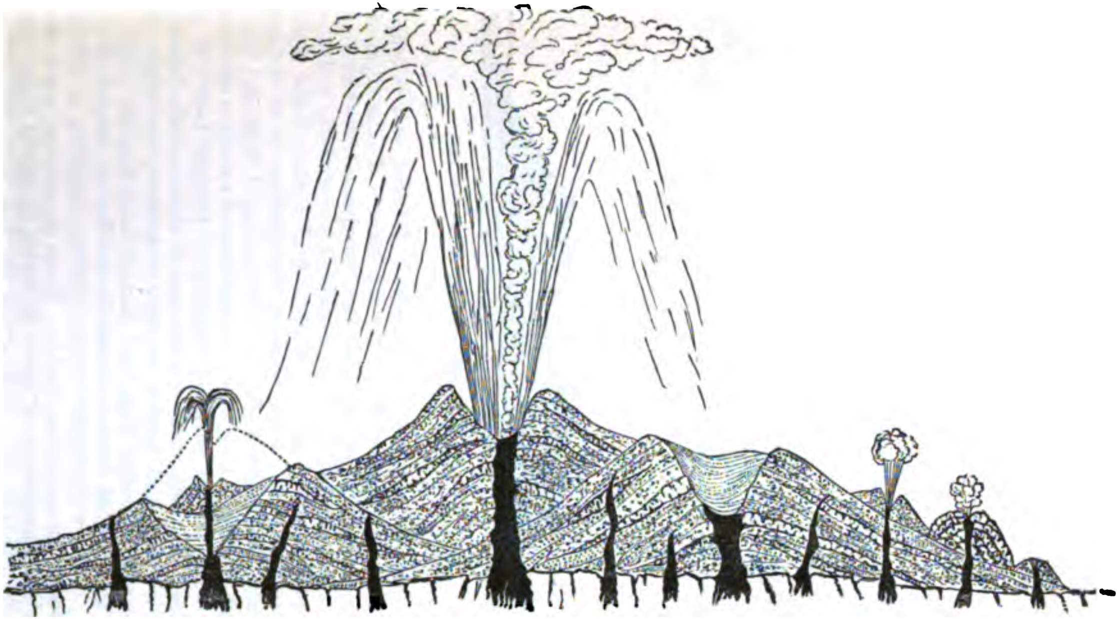

Fig. 36.—IDEAL SECTION OF A VOLCANIC GROUP.
The different patterns have the same meaning as in Figs. 34 and 35.

building up a volcano, is undone by a single explosion. If there be no repetition of volcanic energy after such a catastrophe, the hill retains the form of a truncated, saddle-backed cone; but frequently subsequent eruptions pile up new cones within the old crateral hollows, and the volcano then consists of a truncated mountain with a huge hollow, girt by vertical faces on its inner side, in the middle, and a central peak or peaks standing on the floor of this hollow. This latter form is extremely common and peculiarly characteristic of mountains of volcanic origin.

Fig. 36 is an ideal section of a composite volcanic group formed by the different methods just described. The central cone is in full eruption, and from it the greater part of the discharge is taking place. To the left is a cone of which a large part, shown by dotted lines, has been blown away, and an immense crateral hollow formed: this hollow has been partly choked up with debris, but the eruption in progress has reopened the vent, and is heaping up a new cone within the old crater. To the right of the central cone is an old cone quite quiescent, the chimney of the crater being plugged with hardened lava, and the upper part filled in with debris. Still farther to the right are other cones, each marking the position of a distinct vent. One of these forms a dome-shaped boss and consists wholly of lava; its peculiar form is owing to the fact that the melted rock, of which it is formed, issues in a semi-fluid pasty state, and escapes in thick treacly layers, which cool and harden, as they slide down the edges of the mound, before they have travelled far from the vent.

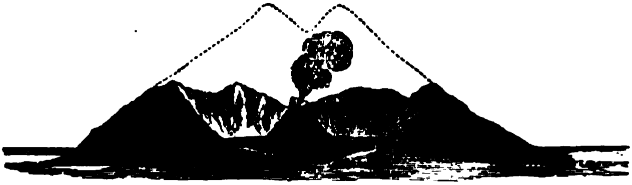

Fig. 37.—Barren Island, after Scrope.

The view of Barren Island in the Bay of Bengal (Fig. 37) shows well several of the alterations in form to which volcanic mountains are liable. Here the original cone, the approximate outline of which is shown by dotted lines, has been breached by a rent which has torn open the valley facing the spectator; it has also been truncated by an eruption which carried away its upper part and blew open the great hollow in the centre: afterwards a repetition of discharges has piled up the still active cone within the hollow.

Subsidence after Cessation of Eruptions.—It seems likely that in many cases after a volcano has become extinct it has subsided to a considerable extent, the sinking having been most considerable around the vent and dying away gradually in all directions outwards. In consequence of this movement the beds around the chimney of an old volcano have been bent out of their original position, and show a dip *inwards* towards the central axis.*

Dispersion of Ash and flow of Lava beyond the Cone: Prolonged Dykes.—So far we have considered only that part of the products of an eruption which go to the building up of the volcano: these however in most cases form only a small part of the whole discharge. The ashes and other ejected materials are often cast forth far over the surrounding country, and, when finely divided, are carried by the wind to enormous distances. The lava streams extend far beyond the base of the cone, covering in some cases hundreds of square miles of country, and even pursuing their course over the sea-bottom. We have not the same opportunities of tracing the extension of dykes, as we have in the case of subaërial products, because they are formed beneath the surface, but there is every reason to believe that they are not confined to the cone itself. In many cases volcanic matter has been observed to be emitted from a number of vents ranged in a straight line for miles across the country; and it seems reasonable to suppose that such points of escape lie on a great underground fissure injected with lava, the cooling of which, on the cessation of the volcanic activity, will give rise to a prolonged dyke, similar to those which may be observed on a smaller scale in the walls of the cone itself. Thus in the eruption of Etna in 1669 "a fissure six feet broad, and of unknown depth, opened with a loud crash, and ran in a somewhat tortuous course to within a mile of the summit of the mountain. It emitted a most vivid light," from which we may conclude that it was filled with melted lava, which on hardening would give rise to a dyke. "Its length was twelve miles. Five other parallel fissures of considerable length afterwards opened one after the other."[*]

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* Darwin, Volcanic Islands, p. 9; Scrope, Volcanoes, p. 225; Heapy, Quart. Journ. Geol. Soc., xvi. 244; Judd, Ibid., xxx. 257; Krug von Nedda, Karsten's Archiv, vii. 247.

A similar case occurred in the eruption of Skaptar Jokul in 1783. "Lava was emitted consecutively at several points on a linear range of two hundred miles. No doubt an underground fissure of this length at least was injected with lava by that eruption, and remains now as a dyke traversing the substrata."[†]

Submarine Eruptions.—Volcanic outbursts take place from the sea-bed as well as on dry land. We have not the same opportunities of examining the former class of eruptions as of the latter, but enough is known to warrant the belief that the two differ in no essential respect whatever. The flow of lava beneath water, though at first sight an unlikely occurrence, has been repeatedly noticed.[‡] At first contact a certain amount of vaporization takes place, but a crust rapidly forms round the lava, which prevents the water coming in contact with the molten interior of the stream, and in consequence of its low conducting power checks the escape of heat. In this way a constantly lengthening tunnel is formed, within which the molten matter pursues its course often to large distances: and if the discharge take place in deep water, it is conceivable that the pressure of the overlying fluid will check the escape both of elastic vapour and of heat from the lava, and so keep it fluid for a longer time, and cause it to spread out in wider and more regular sheets, than if it had flowed out in the open air.

Volcanic Products.—We will now look a little more closely at the products of Volcanic Action. They may be subdivided into—

(1) Molten or Lavas.
(2) Fragmental or Ashes.
(3) Gaseous.

(1) LAVAS.

Fluidity.—The degree of fluidity of lavas varies considerably, but it is rarely, if ever, the case that it is in a state of perfect fusion.[§] Some lavas which have hardened into a glass have probably made the nearest approach to this state, but in the majority of cases fluid lava seems to consist of a mass of crystals and other solid particles enveloped in a pasty, imperfectly fused mass which is permeated throughout by superheated steam and other gases. It is the presence of these elastic fluids that gives to most lavas their apparent liquidity, and the ability to flow in streams; they move indeed somewhat for the same reason as a mixture of sand and water, which will run down a slope on which dry sand would lie.

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[*] Lyell, Principles, 10th ed., vol. ii. p. 21.

[†] Scrope, Volcanoes, p. 52.

[‡] Ibid., p. 92.

[§] "In the case of a metal in a state of perfect fusion, it is conceived that no particle of finite dimensions retains its solidity.

Mr. Scrope has aptly compared lava to "certain stages of the manufacture of sugar, when the matter consists of a soft mass, or 'magma' of granules or imperfect crystals enveloped in a liquid (syrup), which, being subsequently dried by evaporation or drainage, consolidates into a hard substance formed of interlacing crystals."[*]

Of the presence of water in lava there is abundant proof. The column of vapour which rises from the crater during a volcanic eruption, when not carried away by wind, condenses and falls as rain; great clouds of steam rise from the surfaces of cooling lava-flows, and large bubbles can be observed making their way to the top and bursting out in steam-jets with incessant explosions. It is the bubbling up and escape of this vapour that fills lava with the cavities and vesicles that are so characteristic of it, specially over its upper surface. Some of the minerals, too, which occur crystallised in lava have been formed artificially in the wet way, while all attempts to produce them by dry heat have failed; and this is a strong argument in favour of the presence of water in the rock where they occur. Lastly, a microscopical examination of lavas shows them to be full of small closed cavities which still contain water. Some difficulty may at first be experienced in understanding how water can exist in the middle of a mass so intensely heated as lava; a much lower temperature, it might seem, would be sufficient to vaporise it and expel it as steam. But it must be recollected that the temperature at which water is

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In the case of fluid lava, it is supposed that a large portion of the mass consists of small but finite particles, which retain severally their solidity, while their relative mobility is maintained by the remaining portion of the mass intervening in a more perfect state of fluidity between the solid particles, and consisting partly of internal elastic vapours, which by their ascending movements keep the component particles in a constant state of ebullition."—HOPKINS, Report on Elevation and Earthquakes, British Assoc. 1847.

[*] Volcanoes, p. 45; and pp. 121, 122.

converted into vapour depends on the pressure to which it is subjected; increase the pressure, and you raise the boiling point. Deep down in the volcanic focus the weight of the overlying lava will evidently exert an enormous pressure on any water that may be present. Possibly this pressure may be sufficient to keep the water still liquid, in spite of the intense temperature; possibly it may not be able to prevent the formation of steam, but only to check its escape. In the first case, if the pressure be sufficiently relaxed, the water will flash suddenly and with violent explosion into vapour; in the second, under similar circumstances, a mass of high-pressure steam will rush out. When the struggles of the imprisoned vapour to get free have raised the lava sufficiently near the surface to produce the requisite decrease in pressure, one or both of these results is produced, and the explosions from the crater, or the outbursts from the surface of the lava stream, are the result. We must also bear in mind, in connection with the present subject, that there are circumstances under which water, even under an absence of pressure, may be exposed to high temperatures without being vaporised. If water be dropped on highly heated surfaces, it is not converted into vapour if the temperature be sufficiently high, but rolls about in a spheroidal mass and slowly evaporates without boiling. Possibly water may exist within heated lava in this spheroidal condition. It is also known that, when a fluid is shut up in a closed space and heat is applied, the pressure of the vapour produced is able to keep a portion of the fluid still liquid up to temperatures far above its boiling point at ordinary atmospheric pressure. Under such circumstances, M. C. de la Tour raised water to a temperature of 773° F. before it became wholly converted into vapour.

The fluidity of any lava stream will depend on its composition and the temperature to which it is subjected: *cæteris paribus*, lavas of a basic are more easily fusible than those of an acidic composition; hence the former often issue in a state of sufficient fluidity to allow of their flowing to considerable distances, and it is lavas of this class that as a rule form the longest and most extensive streams. The acidic lavas on the other hand furnish the most striking instances of imperfect fluidity; in some cases they ascend in such a thick pasty state, that they consolidate in dome-shaped mounds immediately around the vent; given heat enough, however, even the most highly acidic lavas attain a high degree of fluidity, and give rise to flows of considerable dimensions.

Motion of Lava Streams, and Texture of their different Parts.—On account of its pasty condition and the rapid cooling of its exterior surfaces, the motion of a lava stream differs considerably from that of a perfect fluid. The surface hardens into a crust of slags and cinders, which on account of its low conducting power checks the escape of heat from the interior of the mass, and allows the central part of the flow to preserve its liquidity and capability of motion for long periods. The loose scoriaceous covering is carried forward by the flow of the central fluid portion, and falling over the front of the stream forms a pavement across which the still molten internal portion advances. At the upper surface of the stream also, the bubbling up of the contained elastic fluids fills the hardened crust with cavities and vesicles. The interior portion, which cools slowly and under a certain amount of pressure, is more compact, and as we approach the centre the texture frequently becomes more and more coarsely crystalline. A section of a hardened lava stream accordingly often shows a cindery base, a dense and crystalline centre, and an open and vesicular top. The upper surface also frequently assumes a ropy structure from the slow dragging out of half-cooled viscid portions. We shall see, when we come to the description of the ancient igneous rocks, that some of them present exactly the same peculiarities, and must therefore have been subaërial lava flows.

Where lava is forcibly intruded through other rocks, the pressure to which it is subjected prevents the formation of cindery or scoriaceous texture. The bounding surfaces of the intrusive mass cool too rapidly to allow of the formation of crystals, and are usually dense and compact; the centre, which cools more slowly, shows a more crystalline texture.

But, though there can be little doubt that in many cases it is the rate of cooling which determines whether a lava shall consolidate into a coarsely crystalline or a compact rock, the student must not jump to the conclusion that every coarsely crystalline rock he meets with necessarily owes its texture to its having cooled slowly. There are lavas containing large crystals whose superior coarseness of grain cannot be accounted for in this way, and in which the crystals must have been present in the lava, ready made, so to speak, at the time of its emission. And such a supposition presents no difficulty. We have seen that most, if not all, lavas consist of a greater or less proportion of solid particles enveloped in a mixture of imperfectly melted matter and steam, and, in the lavas we are now dealing with, some of the solid particles are well-formed crystals. There are two ways of accounting for the presence of these crystals. It is possible that, as the lava rises from the intensely heated depths of the volcanic focus into higher and somewhat cooler regions, portions may consolidate and crystallise while the mass remains in a more or less molten condition. Another, and perhaps a more likely, explanation is as follows. We shall see in the next chapter that many rocks have been subjected to a process known as metamorphism, by which crystals have been developed in them, though they were previously non-crystalline. We are very much in the dark as to the exact manner in which the change has been produced; but there is little doubt that three necessary and powerful agents in bringing it about are heat, pressure, and the presence of water. All three of these are at work in the depths of a volcano; and there can be little doubt that the manufacture of crystals by metamorphic action must be constantly going on in the rocks surrounding a centre of volcanic activity. When those rocks are shattered by the throes of an eruption, we can readily imagine that the crystals will be shaken loose, and, falling into the more fluid portions of the lava, will be carried out when it is discharged, and embedded in it when it consolidates. It may not be always possible to say whether the crystals in lava have been formed during consolidation or previously to emission, but we must be careful not to lose sight of the possibility of coarsely crystalline texture having been produced in more than one way.

Composition of Lava.—From a broad point of view there is no essential difference between the mineralogical and chemical composition of modern lavas and that of the Crystalline rocks which resemble them in structure and other respects. Lavas, like Crystalline rocks, have all a Felspar, or a Felspathic mineral, for one of their principal constituents, and show Acidic, Basic, and Intermediate varieties. Perhaps no modern lava is so highly silicated as some of the extreme members of the Acidic class of the Crystalline rocks, and there are certain minerals found in modern lavas which do not occur in the latter. Some geologists have endeavoured to show, on the strength of such facts as these, that the volcanic products of every one of the past periods of the earth's lifetime have each been characterized all the world over by some peculiarity in mineral composition; so that if we find igneous rocks in different parts of the world agreeing in this respect, we may safely conclude they are of the same age. We must hesitate before we accept these conclusions, for several reasons. The facts on which they are based are certainly open to question; the reasoning by which they are supported, involves many very doubtful assumptions; and, what is most fatal to them, they altogether ignore the possibility of gradual change in mineral composition after the formation of the rock. That such changes have taken place we have abundant proof; and, if this point is once admitted, the value of mineral composition as a test of age goes at once.* To take one instance, Leucite is a mineral extremely common in some modern lavas, but for a long time it was believed to be entirely absent from the older Crystalline rocks. A rock, however, has been detected containing Leucite, but the larger number of the crystals have been changed into Orthoclase.† This single observation shows that it is possible that the Felspar of other ancient rocks may have been originally Leucite, and that, though the prevalent mineral of these rocks now differs from that of many modern lavas, it may originally have been the same. We shall have more to say about the apparent want of agreement in mineral composition between the older Crystalline rocks and modern lavas at the end of the chapter.

Texture of Lava.—The varieties of texture of lava are exactly the same as those already described as characterising Crystalline rocks, and we need not therefore repeat the account of them here.

The structure of lava on a large scale falls next to be considered.

Bedded Structure.—When one flow has had time to harden before another has been laid down upon it, lava streams assume a rude sort of bedding; and here we find one exception to the generalization that Crystalline rocks are unstratified. The beds, however, will be wedge-shaped and ill-defined, and more like the irregularly stratified accumulations of shallow water than the evenly-bedded rocks produced by slow and regular deposition of sediment.

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* Allport, Quart. Journ. Geol. Soc., xxx. 529.

† Cotta, Rocks Classified and Described, English Trans., p. 143.

Laminated Structure.—Lavas occasionally show scaly, laminated, or tabular structure, quite distinct from the bedding produced by successive flows. The cause of this structure is believed to be in some cases the frictional drag on the particles as they moved slowly over one another under pressure, and then it is partially analogous to cleavage; in other cases this structure seems to be one produced subsequently to emission, and to be due, like cleavage, entirely to pressure. It is possible that in some cases the divisions may coincide with surfaces of equal temperature, and may have been produced by shrinkage during cooling.

Jointing and Columnar Structure.—Jointing of the ordinary character is very generally present in lavas. But in their case two peculiarities require special notice under this head. In some lavas shrinkage during cooling breaks up the stream into a wild assemblage of irregularly shaped blocks with a surface of indescribable ruggedness. Other lavas possess jointing of a singularly regular and pronounced type, which gives rise to what is known as Columnar or Prismatic Structure. The process of division has been carried out with almost mathematical exactness, and the whole mass is cut up into long prismatic columns of three, four, five, or six sides, neatly fitted into one another. The prisms are divided by transverse joints, and the surfaces of these are frequently alternately concave and convex, so that each column is made up of a number of portions fitting into one another with ball-and-socket joints. The prisms tend to arrange themselves with their axes perpendicular to the cooling surface, so that in a lava stream they are at right angles to the ground, in a dyke at right angles to its walls.

Many attempts have been made to see through the steps of the process by which this structure has been arrived at. The reader will find the latest explanation, and an account and criticism of the most important of those which preceded it, in a paper by Mr. Mallet, in the Phil. Mag. 4th ser. vol. l. p. 122.

Concretionary Structure.—Many lava rocks have a concretionary structure. This is best brought out where they have been exposed to the action of the weather, which breaks them up into a number of rudely spheroidal balls imbedded in the more thoroughly decomposed portions of the rock. The nodules are frequently made up of onion-like concentric coats, which peel off one by one as disintegration goes on. The columnar lavas with ball-and-socket structure pass into the more thoroughly concretionary forms.*

Parallel between Lava and Crystalline Rocks in Structure.—Structures, exactly corresponding to those just described as characteristic of modern lavas, are found among the older Crystalline rocks. All show at times a columnar structure. It is, perhaps, most conspicuous in Basalt, in which rock the columns are thick and regular with equi-distant joints. The prisms of Felstones are slenderer and less regular, and often stretch to a great length without any transverse joints. The same peculiarity has been noticed in Granite, at the Land's End (Transactions Geol. Soc. of Cornwall, iii. 208), in Algeria ("Comptes Rendus," xxvi. 76), and in the Syenite of Ailsa Crag (Macculloch "Western Islands," ii. 493).

Concretionary structure is very conspicuous among Dioritic rocks. Quarries on some dykes in Cornwall are often dug out to a considerable depth through a mass of loose crumbly earth, full of rounded blocks, that at first sight looks exactly like an accumulation of coarse river-detritus. This, however, gradually passes down into solid Diorite, on the exposed faces of which a tendency to break up into concretions is clearly seen to be gradually brought out by weathering; and an examination of the loose capping shows that the incoherent part consists of the more easily decomposed portion of the rock, and that what might be taken for boulders, are the more stubborn concretions.†

Pearlstone and globular Felstones are examples of concretionary structure among Acidic Crystalline rocks. In many of the older rocks this arrangement has been obscured by consolidation, but is brought out again when the rock has been exposed to the action of the air.

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* See the experiments of Gregory Watt, Philosophical Transactions, 1804; De la Beche, Researches in Theoretical Geology, p. 109; Jukes, Manual of Geology, 3rd ed., p. 181; Scrope, Volcanoes, 93; Naumann, Lehrbuch der Geognosie, i. 480.

† I recollect an excellent instance near St. Budeaux, north of Plymouth.

(2) FRAGMENTAL PRODUCTS.

The fragmental products of volcanic action are of two kinds: first the ejected masses of solid pre-existing rock through which the eruption has burst its way; secondly, portions of the melted lava, which have been torn off and tossed up into the air in a melted or pasty condition, and hardened as they fell. Deposits of volcanic ash generally consist of a mixture of both kinds of materials, and vary in grain from the finest and most impalpable dust to coarse accumulations containing angular blocks up to several tons in weight. Thus, to speak first of the coarser ejectments, "by the eruption of Cotopaxi in 1533, the plain around the foot of the mountain was strewed through a radius of fifteen miles and more with great fragments of rock, many of which measured as much as nine feet in diameter" (Scrope, "Volcanoes," p. 55).

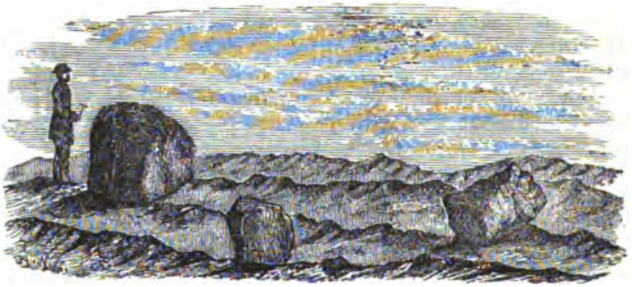

Fig. 38.—LARGE ANGULAR BLOCKS EMBEDDED IN VOLCANIC ASH. NORTH BERWICK.

Similar ejected masses occur in rocks of older date but the same origin. Fig. 38 shows a group of such blocks embedded in stratified ash on the shore near North Berwick. The waves have stripped off the finer and softer parts of the deposit with which these masses were originally surrounded, but boulders equally large and angular may be seen hard by, still enclosed in ashy layers that have not yet undergone denudation. I know of nothing which brings home so forcibly to the mind the enormous energy of volcanic forces as the sight of these huge missiles, and an attempt to realise the power necessary to tear them from their bed and hurl them forth broadcast over the country.

A large portion, however, of the matter thrown out of volcanoes is tossed up over and over again till it becomes broken and ground down to stones, dust, and powder. Out of this finer material, together with the portions torn off the surface of the liquid lava, the greater part of ashy formations are made up; it forms the paste in which the large blocks, when there present, are embedded, or it constitutes the whole body of the deposit.

The following are the chief terms used in describing volcanic fragmentary productions.

Scoriæ are the ragged fragments of lava which have hardened into cinder-like forms.

Bombs are portions of lava which have been thrown out in a liquid state, and, owing to a rapid rotation in their path, have assumed a rudely spherical shape: they are often hollow.

The smaller fragments go by the general name of *Lapilli* or *Volcanic Stones.*

Puzzolana is a name given by the Italians to still finer volcanic powder; and the finest dust of all is called in the same language *Ceneri*, or Ashes.

Structure of Subaerial Ashy Deposits.—The structure and arrangement of deposits formed out of volcanic ejections will vary according as the latter fall on the land or into water.

In the first case there will be an absence or an imperfect degree of bedding, and a tendency more or less pronounced to a confused grouping of the materials.

When a subaërial accumulation of ejected materials contains many large blocks, and when its components are huddled together in a pell-mell way without regard to size, shape, or weight, it forms a *Volcanic Agglomerate;* and if the larger fragments are markedly angular, this peculiarity may be denoted by the qualifying term *Brecciated.* A *Volcanic Breccia* is a rock of similar character, in which the confusion and absence of arrangement is less marked. The finer fragmentary productions, which float through the air often for long distances, settle down more gently and regularly, and give rise to deposits with some appearance of bedding. The finer ashes in their passage through the air often become mixed with water, either rain or condensed steam issuing from the volcano; in this case they cohere more readily when they fall, and give rise to a harder and more compact rock than that formed by accumulations of dry ash. The beds that cover Herculaneum are of this nature.

Ash, too, that has already settled on the ground is often torn up and swept away by torrents of rain, or by floods produced by the sudden melting of snow or the bursting of lakes, and rearranged afresh. In this way a Volcanic Breccia may have its larger fragments rounded and become converted into a *Volcanic Conglomerate;* a pile or cone of fine loose ash may be swept away and spread out in a layer over the district which surrounds it, and will frequently, owing to the admixture of water "set" into a compact rock.

The rocks formed by these admixtures of volcanic ash and water are known as *Volcanic Tuffs* or *Peperinos.*

The term Tuff is, however, by some authors confined to a rock formed when a lava flow is suddenly advanced into water, or is ejected beneath water. In such a case it sometimes happens that the lava is instantly broken up into fragments. Fragmental matter thus produced may often be distinguished from ejected ashes in this way: each grain of the latter is more or less glazed on the outside by the heat of the volcano, the fragments of a lava stream disintegrated by the sudden action of water show no such glazed coating.

Volcanic ash may also be showered over the surface of a lava stream while the latter is still soft, and a rock is then formed of lapilli embedded in a paste of lava.

Structure of Subaqueous Ashy Deposits.—The fragmentary productions that fall into still water will produce rocks differing but little from the more gently formed of the subaërial ashes; but streams, tides, and currents will round and distribute the fragments they receive, and will give rise to Conglomerates and gritty rocks of various degrees of coarseness and with well-marked bedding. These may be distinguished as *subaqueous tuffs.*

It may well happen that water into which volcanic ash is being showered receives at the same time sedimentary materials from rivers that empty into it. In this way there will arise rocks of a mixed origin: when the mechanical sediment is mainly Sand, we shall get an Ashy Sandstone; if Limestone is being formed in the water, there will result a Calcareous Ash; and so on.*

All these fragmentary deposits are capable of enclosing and preserving the remains of plants and animals which lived at the spots when they fell, and such remains are occasionally found in them.

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* For a beautiful example of a volcanic stone embedded in sedimentary deposits, see Geol. Mag., i. p. 24.

Volcanic ashes and tuffs are sometimes described and classified according to the rocks that predominate in their composition. Thus an Agglomerate mainly made up of blocks of Basalt may be spoken of as a Basaltic Agglomerate; a Tuff composed of lapilli of Trachytic lava may be called a Trachytic Tuff. Some of the rocks of this class, however, are composed of such a diversity of materials, that such a system of nomenclature could not be applied to them.

Interbedded with those old Crystalline rocks, which we have learned to look upon as lavas, are numerous deposits, many of the components of which are readily seen to be fragmental ejections from volcanoes. In some cases the ejected matter has fallen on land, and rocks have resulted, resembling in every respect Volcanic Agglomerates, Breccias, and ashy accumulations of finer grain. In other cases the deposit has been of subaqueous origin. Instances will be given in the next section.

(3) Gaseous Products.

The gas given off most largely by volcanoes is steam; they evolve besides Carbonic Acid, Nitrogen, Sulphuretted Hydrogen, Sulphurous Acid, and Hydrochloric Acid. These have probably contributed largely to that alteration of the original volcanic products which will come to be treated of under the head of Metamorphism. Various substances, which are solid at low temperatures, rise in a state of vapour from lava streams; and chemical combinations and reactions between the different emanations give rise to a variety of products, which are condensed on the walls of the fissures and the surface of the flow. Of these we may notice, as geologically important, Sulphur, which is sometimes found in masses of great purity; Specular Iron ore, too, which deserves remark because it forms the colouring matter of red derivative rocks, is largely sublimed from volcanoes, and has probably in many cases been originally of volcanic origin. There are also substances which have been produced, in some cases at least, by chemical reactions between evolved gases and the constituents of the rocks with which they come in contact. The most important of these are Sulphate of Lime, or Gypsum, and Sulphate of Magnesia, which, as we have seen, has probably played an important part in the formation of some Magnesian Limestones. It has been already explained that in many cases both the rocks just named have been formed by precipitation in inland bodies of water, and their materials were probably, in the first instance, derived from volcanic sources.

We must not omit to mention, in conclusion, that volcanic districts abound in hot springs holding in solution Silica and Carbonate of Lime. These have been, in many cases, the source of those chemically formed siliceous and calcareous rocks which have been already described in Chapter IV.

As an instance of a rock which has probably been formed by precipitation from a volcanic mineral spring, we may notice some thin beds of beautifully banded siliceous stone interbedded with volcanic ash on the coast near North Berwick. Their great purity, and the extreme fineness of their lamination, seem to point to a chemical origin; and as they occur in the heart of a great body of volcanic deposits, we may reasonably suppose that their materials were furnished by one of these hot siliceous springs which are so common in volcanic districts. In the same neighbourhood the "Burdie House Limestone" has all the look of a chemical precipitate, and was probably formed in pools into which highly charged calcareous springs emptied themselves. In some cases we can see that volcanic action must have been going on during the growth of this bed, for its upper part is full of small lapilli, which were showered into the water during its formation.

SECTION III.—REMNANTS OF OLD VOLCANOES.

The main features and chief products of the volcanic action of the present day have been now described, and we have seen that many of the older Crystalline rocks and their accompanying fragmental accumulations resemble the latter so closely that there can be no doubt that they were produced by similar agencies in bygone times. We will now inquire whether an examination of the geological record will enable us to point out the site of former volcanic discharges, whether any ancient volcanoes are still recognisable, and generally to what degree of detail we can read the history of volcanic action in the past.

Ancient Volcanic Cones.—We can scarcely expect to find cones of any antiquity often preserved: modern volcanic mountains are already becoming scarred and seamed, by subaërial denudation, and a long continuance of this action must at last wear away entirely the loose materials of which the greater part of a volcano consists, while submergence beneath the sea would sweep it away altogether.

As a matter of fact, however, the number of volcanic hills that still remain in a fair state of preservation, to attest the former presence of volcanic activity in districts where neither history nor tradition give any hint of its existence, is larger than would at first sight be expected. In Auvergne, for instance, the Eifel, New Zealand, and elsewhere, we have not only sheets of solid lava and beds of fragmental ejections, but there are still standing the cones which were piled up round the vents from which these issued, worn and withered indeed by long exposure, but still retaining enough of their characteristic structure and outline to make it evident to the most casual observer that they owe their origin to the same processes which are piling up our modern volçanoes. In all these cases, however, the date of the eruptions, though historically most distant, falls into a late period of geological chronology. As we go back in geological time, we find the remains of the easily destroyed volcanic cone to become rarer and more and more fragmentary, and very soon to vanish altogether.

Remains of Central Plug of Lava.—But even where this has happened, we can still sometimes fix the site of an old volcanic vent: the plug of lava, which hardens in the chimney when a volcano dies out, is of tougher stuff than the cone which surrounds it, and the lower portion of this central cone often remains standing up, like a massive column, when all the rest of the volcanic hill has disappeared.

Other Proofs of Old Volcanic Action.—The records that remain of periods in the earth's history still more remote are seldom perfect enough to enable us to determine the exact spots on which eruptions have burst forth, but among them we find distinct proofs of volcanic activity in the presence of rocks, both molten and fragmentary, of undoubtedly igneous origin. Thus, though the evidence, as we go further back, becomes less and less complete, there is always enough to assure us that during no epoch, of which any history has come down to us, was our earth without volcanoes.

Example of Arthur's Seat.—A very good instance of a fairly well preserved volcano, of still older date than those mentioned a little way back, is furnished by Arthur's Seat at Edinburgh; and, as this is not only an excellent speci-

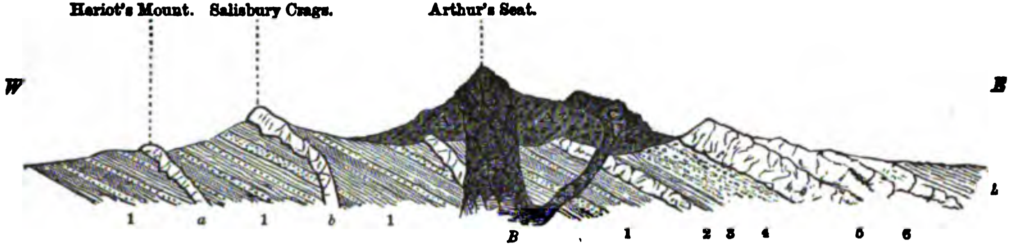

Fig. 39.—Section across Arthur's Seat.

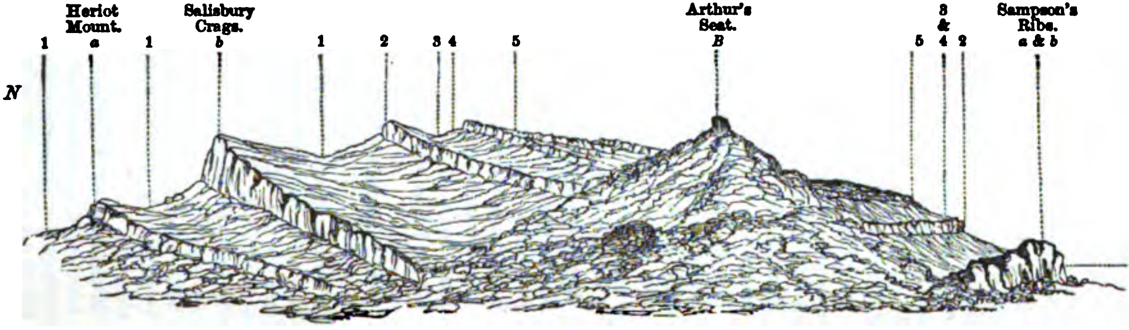

Fig. 40.—Diagrammatic View of Arthur's Seat.

men of its kind, but furnishes an admirable instance of the methods employed by geologists to decipher the records of ancient eruptions and to determine the mode of origin of different kinds of volcanic products, we will describe it at some length.

Fig. 39 is a section of this hill, and Fig. 40 a rude diagrammatic view of its western face. The body of it consists of Shales, Sandstones, fine Conglomerates, and impure Limestone of marine origin, (1) in the figures. Along with these are beds of lava and volcanic ash, formed contemporaneously on the floor of the same sea which received the sedimentary materials of (1). The lowest of these is a sheet (2) of Doleritic rock; then follow Sandstones formed partly of mechanical sediment and partly of ash, which was showered into the water at the same time as sand was brought into it by running streams, and some cherty Limestone (3); above these come well-bedded strata of ejected materials, the components of which were shot out into the water and then arranged in stratified layers, forming a volcanic tuff (4); the series is continued by flows of Basaltic and Felspathic lavas (5) and (6); and these last are covered by purely sedimentary Shales and Sandstones (7).

That the beds of igneous rock in this part of the section were streams that flowed over the bed of the sea, or possibly on land surfaces produced by its temporary elevation, while the deposition of the sedimentary beds with which they are associated was going on, and were not injected among the latter subsequently to their formation, is clear on several grounds. They conform perfectly to the bedding of the rocks above and beneath them, and nowhere cut in the slightest degree across the stratification. Their structure tells the same tale; their upper surfaces are scoriaceous and vesicular, showing that when they cooled the contained gases were free to bubble up and escape: this would not have been the case if they had been covered at that time with overlying rocks as they are now, and they must have hardened before the beds above them were deposited. As we descend into the interior and lower parts of each flow, where there was weight enough of lava overhead to check the ebullition, the cellular structure gradually disappears, and the bed becomes close-grained and compact, and more decidedly crystalline as we approach the centre. In the view the outcrops of the hard lava streams are seen to form steep craggy cliffs, ranging across the hill; while the softer sedimentary beds and ashes occupy the more gentle slopes below these and the hollows between them. The reasons for this will be given in Chapter X.

At some time after their deposition, the beds just described were traversed by sheets of intrusive Dolerite, marked *a*, *b*, *c*. The structure and lie of these contrast forcibly with those of the contemporaneous flows. Their course conforms, to a certain degree, with the direction of the bedding, and in some places they have for a certain space been actually thrust in between the beds, so that a hasty examination of a detached section might lead to the idea that they were interbedded and contemporaneous. But a more careful inspection soon dispels this notion; if followed for a short distance they are found every now and then to eat their way up or down into the strata above or below them. Their intrusive character is also forcibly brought out when the structure of the whole hill is viewed from a little distance. On account of their hardness they crop out in steep craggy cliffs, which, on the north side, form Salisbury Crags and Heriot's Mount; these, as we trace them southwards, instead of keeping the same distance apart, like the interbedded traps, gradually draw together, and at last unite into the single mass of Sampson's Ribs. This union could be brought about only by the sheets cutting obliquely across the bedding. That these rocks are intrusive is also shown by the baking of the beds *both above and beneath* them: the heat of a contemporaneous flow may alter the rocks *underneath* it, but those *above* were not laid down till after it had cooled, and they cannot therefore be affected by it. Lastly, in their structure there is a marked distinction between these and the contemporaneous lavas; they do not possess the cellular upper portion of the latter, but are compact throughout, the cause of this difference evidently being that they consolidated under pressure sufficient to prevent the expansion and escape of their elastic vapour.

The beds described so far were tilted from the horizontal position in which they were laid down, and denuded,* and a hill produced whose outline must have been something like that shown in Fig. 41, and here ends the history of the older portion of Arthur's Seat.

There are, however, other rocks, shown in Fig. 39 by a darker tint, which overlie those already described; these are volcanic, and consist of a mass of very coarse volcanic Agglomerate (*A*), a central pipe of Basalt rising through the Agglomerate (*B*), and a hummock of Basalt (*C*) known as the Lion's Haunch. These are the products of a later eruption. After the course of events which gave rise to the lower part of the hill had been completed, a period of repose followed, and then, at a subsequent epoch, volcanic action broke out afresh. An orifice was torn through the heart of the hill, and from it blocks of the rocks through which a way had been burst were showered out, and piled in a huddled manner round the vent. The Agglomerate is what remains of this accumulation. From the angular nature of its enormous blocks, the pell-mell way in which they lie, and the absence of any trace of bedding, it is clear that it was heaped up in the open air, and the contrast between it and the subaqueous tuff (4) in these respects is most marked and instructive. The Basalt (*B*) is lava, which boiled up in the chimney of the volcano; it can be seen most distinctly running down through the Agglomerate in the form of a rudely cylindrical column. At some time, when there was not pressure enough to drive the lava over the lip of the crater, a tunnel was torn open in the flank of the hill, and through it a flow of lava took place, a portion of which now forms the Basalt (*C*) of the Lion's Haunch.

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* Owing to this denudation we have left only fragments of the old lava flows, and cannot trace them up to the vent from which they issued. It is likely enough, however, that this lay where Edinburgh Castle now stands, and that the castle rock is a plug of lava which fills up the lower part of the orifice.

We have thus still preserved part of the cone of ejected materials and the central plug of this old volcano, but the portion remaining is probably only a small fragment of the original hill. Much of the loose Agglomerate has been carried away by denudation, and the part that is left has escaped mainly because the heat and heated vapours of the vent have baked and hardened it, and enabled it to hold out against atmospheric wear and tear better than the outer portions which underwent no alteration.

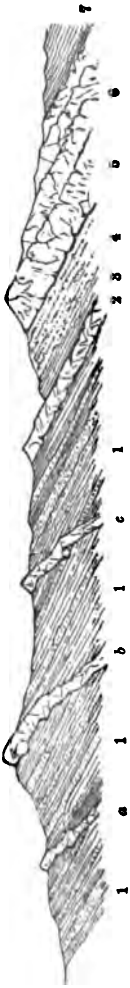

Fig. 41.—The Older Rocks of Arthur's Seat.

In Fig. 40 the conical central mound is formed of the Agglomerate *A*, and at the summit the Basalt plug *B* is seen to rise out of the middle of it. The various members of the older group of rocks disappear beneath the newer formations, and come out again in a corresponding series on the south. On the ground the abrupt truncation of the bed (2), where it has been torn through by the later eruption, can be most distinctly made out.*

Ancient Volcanoes of North Wales.—As an instance of volcanic products of still older date we may take the lava-flows, ashes, and intrusive rocks which make up so large a portion of the mountains of North Wales. We have evidence of active volcanoes at two distinct epochs during the formation of the old rocks, known as Silurian, of that district.

The earliest volcanic products consist of lava flows and beds of ash interbedded with the sedimentary strata of the Arenigs, the Arans, and Cader Idris. These intercalations show in their upper part volcanic ashes and Conglomerate, then a great mass of bedded lava streams, and beneath this a thick body of ash and volcanic Conglomerate: the whole reaches a maximum thickness of between five thousand and six thousand feet.

The volcanic products of a somewhat later date have given rise to the rocks which now form the summit of Snowdon. They consist of the following members:—

Columnar Felstone	200
Ashy Beds	1,200
Slaggy and Brecciated Porphyritic Felstones	1,700

All these rocks furnish most undoubted proofs of a volcanic origin, and of their being of the same age as the sedimentary beds with which they are associated.

The Felstones are sometimes porphyritic, sometimes scoriaceous looking, and sometimes show a decidedly slaggy structure, the lines of viscous flow being as apparent as in the cooled slags of an iron furnace. They are also often most markedly columnar. They conform precisely in their bedding to the sedimentary rocks above and below them; and when they produce any alteration in the associated strata, it is the beds underneath alone that are baked and hardened. Interbedded with the thick masses of Felstone are bands of sedimentary strata, showing that the former are not the results of a single flow, but that they were built up by a succession of streams poured out over the sea bed, and that sediment was laid down in the same water in the intervals between their emission.

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* The explanation of the structure and history of Arthur's Seat given in the text is substantially that put forward by Maclaren, and adopted with some modifications by Prof. A. Geikie. Its correctness has recently been called in question by Mr. Judd (Quart. Journ. Geol. Soc. xxxi. 131). Anything coming from such an authority is entitled to the most respectful attention, but I cannot say that to my mind Mr. Judd has succeeded in showing that the older interpretation is untenable, or even less probable than his own. Mr. Judd's paper, however, should certainly be consulted by the student.

The ashy strata, like the lavas, were accumulated beneath water. They contain a sufficient proportion of slaggy and scoriaceous fragments, and occasionally volcanic bombs, to leave no doubt on the mind that they are formed in large measure of volcanic ejections; but these have in many cases been largely mixed up with sandy, clayey, or calcareous sediment, and in some cases they may have been formed of ashes dropped on land and afterwards carried into the sea by running water. Their submarine origin is further proved by interstratified beds of purely sedimentary origin, and by the occurrence in them of marine shells.

In the case of each of the groups of igneous rocks just mentioned we find them thickest round a certain centre, and, as far as the remnants left of them will enable us to judge, thinning away in every direction from that centre till at last they disappear altogether. We thus get a clue to the quarters in which the vents lay from which the eruptions took place, but all traces of the piles of materials that must have once surrounded these vents have been swept away by denudation. There are, however, great intrusive masses of dioritic rock, which, from their distribution, seem to be connected in some way with both the groups of interbedded Felstones and ashes, and these, perhaps, are the hardened contents of the reservoirs of molten matter from which the volcanoes were fed.* It is worthy of note, however, that while all the undoubtedly contemporaneous volcanic rocks, both molten and fragmental, are felspathic, these deep-seated intrusive masses are markedly hornblendic; and it seems strange that, if the volcanic foci possessed so abundant a supply of hornblendic lava, no sheets of an hornblendic composition should ever have flowed from the craters. The explanation may be that, in accordance with Durocher's ideas, the heavier hornblendic matter sank to the bottom of the reservoir, while the lighter felspathic lavas, floating above, came to be poured out in currents.

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* For details respecting the Igneous Rocks of N. Wales, see Prof. Ramsay's Geology of N. Wales, Memoirs of the Geological Survey of England and Wales, vol. iii.

Did space permit, these instances of beds of volcanic origin among the rocks of the earth's crust might be largely added to; the examples given will, however, suffice as illustrations, and the reader may refer for an exhaustive sketch of the volcanic productions of different ages in Britain to Professor Geikie's Address to the Geological Section of the British Association at the Dundee Meeting of 1867. He should also make an attentive study of Mr. Judd's masterly restoration of the old volcanic area of the Western Isles of Scotland (Quarterly Journal of the Geol. Soc., xxx. 220), and of Mr. Ward's careful description of the volcanic rocks of the Lake district (Ibid., xxxi. 388).

SECTION IV.—PETROLOGY OF VOLCANIC ROCKS.

The comparison which has been now made between the phenomena and products of modern volcanoes and certain members of the Crystalline class of rocks will, it is hoped, have conclusively demonstrated that the latter must have owed their origin to a volcanic source. Our next task will be to look at these rocks on a large scale in the field, to study the different shapes and forms under which they present themselves in mass, to examine their relations to the beds by which they are surrounded, and to inquire how far such observations will guide us to a knowledge of the circumstances under which they were formed.

Distinction into Intrusive and Contemporaneous.—The molten products of igneous action are in the first instance forced up through apertures torn through the surface of the ground, and forcibly injected into cracks and rents which afford a passage for their escape, and they must also exist in large masses in cavities below the surface. When the contents either of an aperture, a crack, or a cavity cool and harden, bodies of crystalline rock will be formed; these will evidently assume different external shapes in the three cases mentioned, but they will all agree in one point—they will all give proof of having burst through the rocks which surround them; hence they are all classed together as *Intrusive.*

The columns of cooled lava which fill up an old volcanic chimney are known as *Necks;* the hardened contents of cracks form *Dykes* or *Veins*, the term Dyke* being restricted to those fissures which are approximately rectilinear and vertical, while the more irregular tortuous or branching rents give rise to Veins. The solidification of the molten masses of cavities produces large amorphous *Masses*.

It is clear that any mass of intrusive igneous rock must be of later date than the rocks it traverses, hence intrusive igneous rocks are also spoken of as *Subsequent*.

But the molten matters poured out from volcanoes also present themselves to us under another form. Great sheets of lava flow from the vent and spread themselves over the surrounding district. These stream *over* the pre-existing rocks instead of bursting through them, and they therefore stand somewhat in the same relation to the rocks beneath them as an overlying stratum of sedimentary material, and are in this respect clearly marked off from rocks of an intrusive character. Lava sheets poured out on dry land may be lowered beneath bodies of water and sedimentary rocks laid down above them; or it may happen that, after a mass of derivative rocks has accumulated beneath water, a subaqueous stream of lava may flow over them, and be in turn itself covered by further depositions of sediment. In these ways there will arise formations consisting of alternations of beds of molten and sedimentary origin, the rocks of both classes being truly interstratified and perfectly conformable in their bedding to one another. An instance of a formation of this sort is furnished by the older rocks of Arthur's Seat, shown in the section on Fig. 39. Igneous rocks formed under these circumstances are called *Interbedded*, or, because they were formed at the same time as the sedimentary beds among which they are found, *Contemporaneous*. Now, in studying any mass of igneous rock we may come across in our investigations, the first thing to be made out is, to which of these two classes does it belong. Is it Intrusive or Contemporaneous?

In many cases there is not room for a moment's hesitation on this point: a cylindrical pipe drilled through bedded sedimentary strata, or a rent torn across them at right angles to the bedding, and filled up with hardened lava, furnish conclusive proof that the latter is intrusive. And at first sight it might seem equally safe to pronounce that a lava sheet, lying between two masses of sedimentary strata with its upper and under surfaces parallel to the bedding of the rocks above and beneath it, was undoubtedly contemporaneous. But such a conclusion would not necessarily hold good, because there are cases when lavas have been forcibly intruded *between the planes of bedding* of pre-existing sedimentary rocks, and where they have confined themselves so strictly and for such long distances to the space between two consecutive beds, that a delusive appearance of true interbedding is produced. In the case, therefore, of a lava *sheet* much care is often needed before we can decide whether it is intrusive or contemporaneous; some of the tests which decide the question have already been hinted at in the description of Arthur's Seat, and the subject will be more fully treated of further on.

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* "Dyke" means in north country language a wall. The contents of igneous dykes are usually harder than the rocks they traverse; hence the latter are more easily and largely removed by denudation than the former, and a rib of the more durable rock is left standing up, running like a wall across the country.

Alteration of Neighbouring Rocks.—One fact which will aid us in clearing up such doubtful cases, and which we shall also have occasion to refer to in connection with other branches of our subject, is the alteration wrought by the intense heat of lavas in the rocks they come in contact with. Soft Clays are baked into hard, flinty, porcelain-like rock; Sandstones are hardened and rendered crystalline; Limestones are turned into marble; Coal is converted into cinder or soot. Owing to the low conducting power of rocks, such changes seldom extend to any great distance from the margin of an igneous mass; and sometimes the rocks immediately in contact with the once molten matter are perfectly unaltered. The absence of alteration is easily explained, if we recollect that the chilling effect of the surrounding rock would rapidly cool the layer of fused matter immediately in contact with it, and a crust would thus be formed which would separate the still liquid central portion from the rocks on either side and prevent the passage of heat from one to the other.

Included Fragments.—Intrusive rocks too frequently tear off and carry along with them fragments of the rocks through which they have forced their way; such detached portions vary in size from mere stones up to large masses. They are usually baked and hardened. Fig. 42 shows a case of this sort seen on the castle rock at Dunbar. A mass of Greenstone (1) has burst through Sandstones and Shales (2);

the former are altered along the line of junction into a hard crystalline Quartzite (3), and in the very middle of the greenstone is a wedge-shaped mass of similar Quartzite (4), evidently a large fragment of the Sandstone, through which the intrusive rock was ejected, caught up by the liquid lava, baked by its heat, and retained in its midst when it cooled.

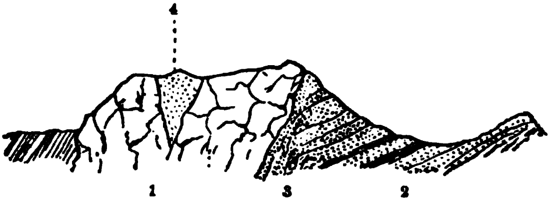

Fig. 42.—Section at Dunbar Castle, showing an included mass of altered Sandstone in Greenstone.

It sometimes happens that subaërial lava streams, too, contain included blocks. If they flow over ground covered with loose fragments, some of these may be caught up and embedded in them, or blocks of rock may have been thrown out of a volcanic vent, fallen on the surface of a lava while it was yet soft, and sunk down into the body of the rock.

Fragmental Interbedded Rocks.—The fragmental products of volcanic action give rise to rocks which are necessarily for the most part of an interbedded character; deposits, namely, of stones, cinders, and lapilli shot into water and arranged in layers alternating with beds of purely sedimentary origin, or to strata formed of a mixture of volcanic ash and sediment.

Necks of Agglomerate.—But it sometimes happens that the chimney of a volcanic vent has been filled in, not with hardened lava, but with a confused mass of volcanic ejections, which have fallen back into it after they were hurled into the air. We thus get *Necks of Volcanic Agglomerate*, where the latter stands to the surrounding rocks in the same relation as a plug of intrusive molten rock. Such masses, though they can hardly perhaps be called intrusive in the proper sense of the word, are clearly distinguishable from the truly interbedded deposits of volcanic ejections.

Instances of the Modes of Occurrence of Volcanic Rocks.—We will now consider a little more in detail the different forms under which we have seen that large bodies of volcanic rock present themselves. These may be classified under the following heads: Masses, Dykes and Veins, Necks, and Sheets.

Masses.—One form under which Crystalline rocks occur is that of large masses, sometimes many square miles in extent; they are occasionally approximately circular or elliptical in shape, but frequently their outline is most irregular.

Fig. 43, which shows a ground plan of a boss of this kind in the north-west of Ireland, and a section

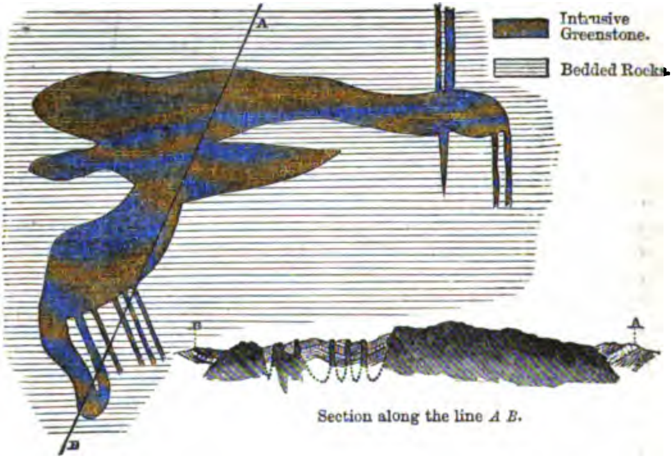

Fig. 43.—Plan and Section of Intrusive Greenstone Mass, Co. Donegal, Ireland.

Scale 2 inches to a mile.

across it, will give an idea of the character of these igneous masses. It is highly probable that masses such as we are now considering are in many cases the hardened contents of reservoirs of lava, which existed originally deep down in the bowels of a volcanic area, and which have been brought to light by the denudation of the rocks which covered them. But very many of the largest Crystalline masses may be pronounced almost with certainty to be the result of the alteration by heat and other agents of rocks originally sedimentary, because they are found to pass by insensible steps into rocks of that class. As one instance we may mention large masses of quartzose porphyritic trap in the neighbourhood of Llanberis, on the borders of which such a passage is found to occur.*

Dykes and Veins.—It has been already mentioned that modern volcanic cones are frequently torn across by rents approximately vertical, which are afterwards filled in with lava; ribs of igneous rock, exactly similar in character, are constantly met with cutting across the older rocks of the earth's crust. Sometimes these can actually be seen to be offshoots from a large igneous mass: this is the case in Fig. 43, where many dykes are seen running out from the main body of the trap into the surrounding country. More frequently, however, the connection of these older dykes with the parent mass can no longer be traced; they have been either severed from it by denudation, or they descend deeper into the earth than we can follow them before they reach it.

Dykes are found of all dimensions, both in length and breadth; they vary in thickness from less than a foot upwards; and while in some cases the portions of them that appear at the surface do not extend longitudinally for more than a few yards, in others they can be traced continuously for miles.

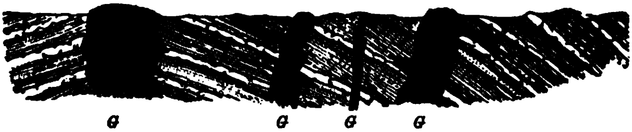

Fig. 44.—GREENSTONE DYKES CUTTING THROUGH SHALES AND LIMESTONES, WEST OF DUNBAR.

The section on Fig. 43 shows dykes with remarkably true and even walls; Fig. 44 is a sketch of a group of dykes (*G*) more irregular in outline, cutting through Shales, Sandstones, and impure Limestones, and sending tongues out into them.

Necks.—A good instance of a plug of hardened lava filling up an old volcanic vent has been already given in the section of Arthur's Seat in Fig. 39. In this case the neck is still surrounded by part of the cone which it traversed; more frequently, however, the softer and friable surrounding of fragmental matter has been carried away by denudation, and the central column of hard lava, or the lower portion of it, alone remains to fix the position of the orifice. These remnants of the plugs that once filled volcanic vents are very common among the old volcanic rocks of the central valley of Scotland. Some good instances may be seen on the Berwickshire coast, where isolated bosses of porphyritic Felstone stand up in low hills above the softer rocks of the surrounding country.* When these are examined they are found to be rudely cylindrical columns which descend vertically through the surrounding strata. There are also in the same district lofty conical-shaped hills—Trapain Law and North Berwick Law for instance—composed of a similar rock. We cannot prove by actual inspection in these latter cases that the eminences are the summits of great cylinders that pierce through the beds around them; but such a supposition is highly probable; and we may very fairly look upon these prominent peaks as probably portions of the column of lava that rose through a volcanic orifice, their size being due partly to the fact that the volcano was a big one, and partly to their having formed a portion of the column where the orifice was roomy. These necks usually project above the surrounding rocks for the same reason that dykes stand up in walls, because they are the harder of the two.

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* The Geology of North Wales, Memoirs of the Geological Survey of England and Wales, vol. iii. chap. 20.

But we have already mentioned that a volcanic vent is sometimes filled in, not with hardened lava, but with a mass of Volcanic Agglomerate. A capital instance in Ayrshire, described by Professor A. Geikie,† is illustrated by Fig. 45.

The section runs across a basin consisting of the following rocks. At the bottom are Shales and Sandstones (*a*); upon these rest some beds (*b*) which consist of irregular alternations of volcanic ash and brick-red Sandstone. Then come sheets of lava (*c*), consisting of Labradorite and specular Iron ore, with sometimes a little Augite. These are covered by beds (*d*) similar in composition to (*b*). Above all there is a group of brick-red Sandstone (*e*), containing in its lower part occasional nests of volcanic lapilli and single stones.

From this section we learn that the district was free from volcanic activity during the deposition of the beds (*a*). The next beds (*b*) show the commencement of eruptions;

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* The Geology of East Lothian (Memoirs of the Geological Survey of Scotland), p. 40.

† Geol. Mag., iii. 243; Memoirs of the Geological Survey of Scotland, Explanation of sheet 13, paragraph 5, and of sheet 14, paragraph 26.

they were formed partly out of sandy sediment, and partly by showers of volcanic dust and lapilli, which fell into the water where the silt accumulated. Then came the emission of the lavas (*c*). These present all the peculiarities which we have described as characteristic of contemporaneous flows; they are divided into beds with slaggy or cindery upper and under surfaces, and sometimes parted from one another by layers of brick-red Sandstone. Running across these lavas in a direction perpendicular to the stratification there are what look like veins of horizontally bedded red Sandstone, which sometimes radiate from a centre forming star-shaped figures. These were doubtless produced in the following manner. As the lava cooled cracks opened in its surface, and sand was washed into the cracks and filled them up before they were covered by the next flow. The absence of lava sheets in the beds (*d*) shows that volcanic activity was on the decrease during their formation, and its final cessation is indicated by the gradual disappearance of volcanic products as we pass from the lower to the upper part of the group (*e*).

In the country occupied by the beds (*a*) there are a number of small rounded hills or hillocks, two of which are shown at (*f*) and (*g*). These consist of a very coarse red volcanic Agglomerate, unstratified and tumultuous in appearance, made up of fragments of lava similar to (*c*), of all sizes up to masses a yard or more in length, angular, subangular, and rounded, imbedded in a gritty, felspathic, ferruginous paste. These hillocks rise conspicuously above the neighbouring ground, and might at first sight be taken for the remnants of a deposit which once extended over the beds (*a*), the greater part of which has been removed by denudation; but such is not the case. Though surrounded by the Shales and Sandstones, they do not lie on the latter; on the contrary, they descend vertically through them. like so many huge pipes. In short they are true

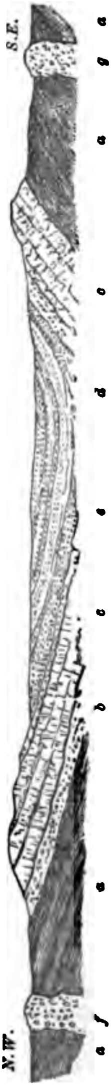

Fig. 45.—Section across the Permian Basin of Ayrshire. (After Prof. A. Geikie.)

volcanic necks, each representing a former focus of eruption. In one case the sides of a neck were found coated with a lining of rough slaggy lava, which had clung to them during the discharge of a stream of molten matter.

The close neighbourhood of these vents to the volcanic rocks of the section, and the similarity between the blocks they contain and the lavas (*c*), makes it almost certain that it was from these orifices that the volcanic products of the adjoining rocks were discharged.

For other instances of necks of volcanic Agglomerate see the Geology of East Lothian (Memoirs of the Geological Survey of Scotland), p. 44.

Sheets.—The only remaining form under which igneous rocks occur, is that of sheets, and these are, as has been already mentioned, of two kinds, intrusive and contemporaneous.

Intrusive sheets, like dykes, are merely hardened masses of lava, which were forcibly injected in a molten state into rents traversing pre-existing rocks; but while we restrict the term dyke to those cases where the fissure is vertical or cuts across the bedding at large angles, we use the word sheet where the cleft is inclined at small angles to the bedding, or where the actual space between two beds has furnished a channel for the molten matter. The difference in appearance between the two forms is quite enough to justify us in using the two names; and it is besides desirable to keep up the distinction, because, whereas no one could suppose a dyke to be anything but intrusive, those sheets which have been thrust in along the planes of bedding are liable to be mistaken for contemporaneous flows.

A contemporaneous sheet is formed by the flow of a lava stream over the bottom of a body of water on which sedimentary deposits have previously been laid down, and by the subsequent formation on the top of the stream, after it has cooled and hardened, of other accumulations of sediment.

Where an intrusive sheet cuts across bedding planes, its true character is at once recognised; but where a sheet occupies the space between two beds, it requires some care to determine to which class it belongs. The tests to be applied in such a case have been some of them already mentioned and may be summarised as follows:—

1st. Alteration of the adjoining rocks. A contemporaneous sheet can produce alteration *only in the beds below it*, because those above were not laid down till after it had cooled. An intrusive sheet can alter the *beds above as well as those below* *it.* We must recollect, however, in applying this test, that the absence of alteration proves nothing, because igneous rocks sometimes produce no change in the beds they come in contact with. If the beds above as well as those below an igneous sheet are altered, we are sure it is intrusive; if those below only are affected, it yields a presumption that it is contemporaneous, but other tests must be applied before we can be certain it belongs to this class.

2nd. Texture. The rocks which now overlie a contemporaneous sheet were not there when it was poured out, and there was no pressure on it from above at the time it cooled. Its upper surface will therefore be liable to have a ropy or scoriaceous texture, or to be full of bubbles and cavities produced by the escape of the contained gasses. The vesicles are often elongated in the direction of the flow, having been dragged out by the motion of the stream. Its base, too, like that of a recent lava stream, will often be cindery. It will be only in the centre that there was pressure enough to give rise to a closely grained texture. But an intrusive sheet was weighed down from above by the overlying rock at the time of its injection, and the compression thus produced prevented any part of it from assuming a loose and open texture; the upper and under surfaces may, on account of their more rapid cooling, be fine-grained, while the slower hardening of the interior may have allowed of the formation of more largely crystalline products; but though for these reasons different parts of it may differ in grain, the whole of it will be dense and compact, it will rarely show scoriaceous portions, and if it be at all vesicular, the cavities will be neither numerous nor large.

3rd. Relations to the bedding of rocks above and below. A contemporaneous sheet cannot evidently cut across or eat its way into the beds above it, because they were not there when it was poured out. It is possible that, in its passage over the underlying strata, it might disarrange and perhaps work down into them, but this could take place only to a very small extent. We may say of such sheets that their upper and under surfaces are *everywhere* parallel to the bedding of the rocks above and beneath them. This will not be found to be the case with intrusive sheets; they have sometimes pursued their path with wonderful constancy along planes of bedding, so much so that the examination of a limited exposure might lead to the belief that they were interbedded; but if followed out they will invariably be found sooner or later to cut up or cut down into the rocks above or beneath, or to send out tongues or spurts into them, and somewhere to break across the stratification in a way that at once reveals their true character.

4th. The presence of included blocks may sometimes decide whether a sheet is intrusive or contemporaneous; if these have come from the overlying rocks, the sheet must belong to the former class.

The third test is perhaps the one of most universal application. Texture alone cannot be relied upon, and alteration of the adjoining rocks may be wanting; but an intrusive sheet will seldom fail to show its real nature somewhere or other by pursuing a course transgressive to the bedding of the rocks among which it occurs.

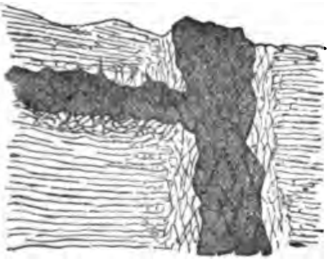

Fig. 46.—Dyke and Intrusive Sheet of Dolerite.

In the account of Arthur's Seat a few pages back, the application of these tests to a particular instance was pointed out, and Fig. 46 is a section on the coast west of Dunbar which further illustrates the subject. Let us confine our attention first to the left-hand half of the figure. We see there a sheet of Dolerite shown by the dark colour, apparently interbedded with a group of Shales, whose bedding is shown by the fine parallel lines. The upper and under surfaces of this sheet are so far parallel to the bedding of the Shales, that it is not apparent at first sight to which class it belongs. Let us apply the tests just given to determine its true character. In the first place the beds *both above and below* are markedly altered; the Shale, which a few feet off the Crystalline rock is so soft and clayey that it yields readily to the impress of the finger, is baked into a hard, flinty, felsitic rock, which will scratch glass, and has here and there a slightly crystalline texture. Hand specimens of this altered Shale could not be distinguished from a compact Felstone. Next, in spite of its rough conformity to the bedding, we find, when the junctions are closely scanned, that the rock has thrust out bosses and strings, giving it rough and irregular boundaries very different from the even planes of bedding of the Shale. The floor of the stream, too, gives unmistakable proof of rough usage; the beds of Shale have been puckered and crumpled, and the uppermost of them broken up into small bits, which are tilted on end against one another, so that the line of junction has a jagged, saw-like edge.

By all these signs, then, we are sure that the sheet is intrusive, and our conclusion is confirmed when we trace it towards the right, for we then find it springing out from a dyke, which cuts vertically across the bedding. This dyke has caused great alteration of the rocks on either side; they are baked into a Felsite, such as lies above and below the sheet, and their bedding becomes gradually effaced as they approach the Dolerite, and replaced by a rude jointed or platy structure with divisional planes parallel to the walls of the dyke.

The above is a happy case, where we find all the tests which distinguish an intrusive from an interbedded stream exhibited. The observer must not expect to be always equally lucky, some one or more of the marks of distinction are often absent; the igneous rock, for instance, may not have given rise to any alteration of the beds it traverses, and we may thus miss one of the easiest ways of determining its nature. He must then fall back on another test; and there are very few cases indeed, in which, when all the circumstances have been taken into account, any uncertainty will remain.

Subdivisions of Igneous Rocks into Volcanic and Trappean.—It was mentioned in the beginning of this chapter that many of the Crystalline rocks resembled so closely in every respect the subaërial molten products of modern volcanoes, that there could not be a shadow of a doubt that they are ancient lavas; and that others, which bear evident marks of having been produced by the action of heat, still differ in some essential respect from the lavas of the present day. The first class are usually distinguished as Volcanic, and the second as Trappean. Under the first head come the slaggy, cindery, and amygdaloidal Crystalline rocks; while the second includes Diorite, many compact Felstones, Granite, Syenite, and other allied rocks.

We will here point out the main points of difference between the two classes, and see how far certain generalizations, which some authors have attempted to base on these differences, appear to be sound. The subject cannot be fully gone into till we have given a more complete description of the Trappean rocks; but it may be as well to mention here the broad results we shall finally arrive at.

1st. The Volcanic rocks are, as a rule, anhydrous, or free from water, and have the cellular, scoriaceous, slaggy, or ropy texture, which is exhibited by lava streams that have cooled and hardened in the open air; the Trappean rocks are usually hydrated, and compact in texture.

This distinction is a valid one, and its meaning is evident enough. The rocks of the first class are subaërial, and the absence of pressure allowed of the escape of the steam, which all lavas contain at the time of the ejection, and of the formation of those structures which melted matter is apt to assume when it cools under an absence of restraint. The rocks of the second class were consolidated under pressure, beneath either a mass of overlying measures or the water of the sea; and thus their water was prevented from escaping, and they were not free to boil up or drag themselves out into spongy or slaggy shapes. That the two kinds of rocks had a common origin, and differ only because they were formed under different circumstances, is proved by the existence of numerous intermediate forms, which show a passage by almost insensible gradations from the extreme of one class to the extreme of the other.

2nd. It is also stated that there are certain mineralogical distinctions between the two classes. The minerals of the Volcanic group are usually glassy, those of the Trappean dull and opaque. Thus among Acidic Crystalline rocks, Sanidine or glassy Orthoclase is supposed to be confined to the Volcanic, common Orthoclase to the Trappean class. In the Basic class, both Hornblende and Augite, but principally the former, occur in Trappean rocks, but only the latter in Volcanic rocks. Also Trappean rocks are said to be richer in Silica than Volcanic.

There are certainly exceptions to these generalizations;* but, allowing them to be true in a general way, it seems difficult to attach much value to them. From a merely mineralogical point of view they may have some interest; but, when we reflect on the very minute character of the distinctions, and further consider that the one class of rocks are, as we shall immediately mention, in many cases older than the other, it is difficult to resist the suspicion that such differences may be no more than the result of time. The supposed greater richness in Silica of Trappean rocks may, for instance, be readily explained by supposing that substance to have been deposited by water percolating through them during the long lapse of time that has passed since their formation; or by the removal, by percolating water, of their more soluble constituents, and the retention of the less readily dissolved Silica.*

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* For instance, the Trachytes of Sardinia of post-Eocene age, which contain Hornblende (General de la Marmora, Voyage en Sardaigne, 3me. pt. tome i. chap. xiv.); a very ancient lava on Cader Idris, with crystals of glassy Felspar (Ramsay, Geology of North Wales, p. 28).

3rd. We come to a far more important generalization, which some geologists attempt to maintain in connection with the present subject.

It is asserted that the older igneous rocks are Trappean in character, while those belonging to the more recent geological periods and those of modern date are Volcanic; and an attempt has been made to lay down rules, based on this statement, by which the age of an igneous rock may be determined by its mineral character alone.

The above assertion is correct in many cases—in so many, indeed, that there is no wonder that it was assumed to be universally true; at the same time there are exceptions enough to it completely to upset the generalization attempted to be drawn from it. In the first place, that Trappean or deep-seated rocks should be more numerous among the older deposits, and that Volcanic or subaërial rocks should prevail among those of younger date, is only what is to be expected; for subaërial products of any antiquity could only by a lucky chance escape the destructive action of denudation, and must therefore be rarer than those deep-seated products which have been better protected from its action; while in the case of the newer formations denudation has not yet had time to carry away the lavas, ashes, cones, and other external products of volcanic action, and, by the removal of these and the masses of rock underlying them, to lay bare the formations that have hardened far down in the bowels of a volcanic area. In short, the generalization amounts to no more than this: the older igneous rocks are mainly deep-seated, because denudation has largely carried away the subaërial igneous formations of distant epochs; newer igneous rocks are mainly subaërial, because denudation has not yet worked its way down to the deep-seated formations of recent periods.

We must also bear in mind that the changes which time is always producing must necessarily cause a difference between a rock of comparatively recent and one of very

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† Sterry Hunt, Quart. Journ. Geol. Soc. of London, xv. 493.

remote date; and this may be the explanation of the mineralogical differences between Volcanic and Trappean rocks mentioned under the second head.

It will be sufficient to notice only one or two of the numerous exceptions to this third generalization. In the Lake country of England there is a group of rocks known as the "Green Slates and Porphyries," which were probably in part of subaërial volcanic agency. Many of these —allowing maybe for a little, but a very little, degree of hardening—cannot be distinguished from modern cellular lavas, and, tried by the tests mentioned above, would certainly be placed in the Volcanic class, but they date far back in the geological record. Again, among the sheets of igneous rock which occur in the Scotch Carboniferous beds, a formation of great antiquity, it is the commonest thing to find some with a cindery base and slaggy top, exactly such as characterize modern lava streams. Such instances might be multiplied, if it were necessary, without limit. The reason why subaërial rocks, in cases like these, have survived through such long periods is, that shortly after their emission they were covered up by sedimentary beds, and so preserved from the destructive effects of denudation.

The distinctions, then, between the two classes, as far as they are well founded and of any real value, are due mainly to the different circumstances under which the rocks belonging to each were formed, partly, perhaps, to changes they have undergone since the date of their formation. They are, therefore, accidental and of comparatively little moment; but if we turn to the grounds of resemblance between the two classes, these are seen to be far more numerous and important, and to point forcibly to a common origin for the rocks of both.

The term Plutonic* is used by many authors in the sense which has been here assigned to Trappean; others are inclined to group together Granite and its allies in a class by themselves, to which they give the name Plutonic. We shall see, however, by-and-by that there is no hard line between Granitic rocks and those usually designated as Trappean, any more than between the latter and volcanic products.

All three terms may be usefully employed, if we only bear in mind the only sense in which they can properly be used. They denote simply the conditions under which an igneous rock has been formed. If we could follow a sheet of such rock continuously from the external lava flow through the volcano down into the reservoir from whence it issued, we should doubtless find at different points instances of the three types passing gradually into one another. The subaërial discharge, with all its characteristic accompaniments, would gradually lose these and put on a Trappean form as we penetrated into the bowels of the volcano; and still deeper down the Trappean type might become so much more markedly pronounced, that the rock might deserve to be distinguished as Plutonic. But there would be no hard lines between the three subdivisions, and hence in nature we often meet with rocks that puzzle us to say to which we ought to refer them. This subject will be more fully handled in Chapter VIII.

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* From Pluto, the god of the underground realm, because these rocks have solidified deep down beneath the surface.

A speculation has also been put forth that the older igneous rocks are mainly Acidic and the newer mainly Basic in composition.* There is much to be said from a broad point of view in favour of this idea, but at the same time there are many facts directly in the teeth of it.† It is mentioned here mainly because geologists of high repute have been found to countenance it.

Some authors hold a similar opinion, but under a modified form. Thus Cotta says, "We are almost justified in holding it for a universal law that whenever igneous rocks rich in Silica occur together with Basic igneous rocks of the same period of eruption, the latter are of somewhat later origin than the former."‡ This notion has an *à priori* probability in its favour, for it is likely that the lighter Acidic products would be discharged before the heavier Basic, and cases may doubtless be found where the rule is true; but there are also exceptions enough to it to prevent our accepting it as a universal law. (See Scrope's "Volcanoes," pp. 125 and 347.)

Other attempts have been made by chemists and petrographers to discover a connection between the mineral character of an igneous rock and the date of its formation, but they have all broken down when subjected to the test of geological examination in the field.

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* Durocher's Essay on Comparative Petrology. There is a translation in Prof. Haughton's Manual of Geology.

† See Scrope's Volcanoes, p. 128; Allport in Geological Magazine, vol. x. p. 196.

‡ Rocks classified and described (English translation), p. 187.

CHAPTER VII.

METAMORPHIC ROCKS.

> "Was the world not made at once then?" said Felix.
> "Hardly," answered Jarno; "good bread needs baking."
> WILHELM MEISTER'S TRAVELS.

SECTION I.—GENERAL VIEW AND INSTANCES OF METAMORPHISM.

General Description.—The rocks we have hitherto considered, both of the igneous and derivative class, have come down to us pretty much in the same state in which they were originally formed. Time indeed has not passed over their heads without leaving its mark upon them in various ways; they have been hardened, new minerals have been introduced into them, and they have undergone other changes of a similar nature. But in all the cases that have so far come under our notice the utmost amount of alteration that has been effected does not amount to much; the characters we rely upon as indications of origin may have been disguised to a small extent, but no rock we have yet met with has been so thoroughly transformed that we are no longer able to say without hesitation how it was produced and what was its original nature.

The minor modifications, however, we have already become acquainted with, will suggest to us the possibility of there being rocks which have been altered to a much greater degree; and observation shows us many rocks whose peculiar character can be explained only on such a supposition. To these we shall devote the present chapter.

The process by which changes are wrought in a rock after its formation is called *Metamorphism*, and rocks altered by its action are distinguished as *Metamorphic Rocks*. Strictly speaking, it would be hardly possible to find a rock which is not metamorphic to some degree, but the term is usually restricted to those rocks which have suffered transformations of so radical a nature, that it is only by long and attentive study that we become convinced they are merely the altered forms of some of those rocks we have become already acquainted with, and only by calling in the aid of the chemist and mineralogist that we can form any reasonable conjectures as to the processes by which the alteration has been effected.

It will be as well, before we come to a formal description of the rocks usually classed as metamorphic, or indulge in any speculation as to the causes to which metamorphism is due, to lay before the student a description of one or two districts in which rocks of this class occur. In this way he will at the outset become acquainted with the nature of the evidence on which geologists base their belief in the metamorphic character of the rocks in question, and will see that it is on broad geological grounds that they are led irresistibly to this conclusion. It will appear that, when rocks of this class are studied in a large way in the field, they are found to possess on a great scale many of the distinguishing characters of derivative deposits. They consist of alternations of rocks of different character and composition, just as in sedimentary beds we meet with alternations of Shale, Sandstone, and Limestone. The several members are laid in regularly bedded order one upon another, and range over the country according to the direction and amount of their dip. Among them we occasionally find beds still retaining their fossils, conformably placed with regard to the strata above and below them, and evidently forming part of the same series.* Some of the minor peculiarities of derivative deposits are, moreover, still to be detected in rocks of this class. Thus Mr. Sorby has recognised in Mica-schist exactly the same ripple-drift structure which we have already seen is so common in Sandstone.† Lastly, we occasionally meet with transitions of the most gradual character between these rocks and stratified fossiliferous deposits, the two melting imperceptibly into one another. From extensive observations of this nature, we arrive at the conclusion that the rocks now under consideration were originally sedimentary deposits, and that they have been subsequently altered so as to acquire a crystalline texture and certain structural peculiarities.

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* Murchison, Siluria, pp. 163—169; Russia and the Oural Mountains, 402, 438, 465; Brochant, Annales des Mines, 1st series, vol. iv.; Leonhard's Jahrbuch, 1840, p. 352.

† Quart. Journ. Geol. Soc. of London, vol. xix. p. 401.

When we have thus seized on a clear view of the general nature and probable origin of the metamorphic rocks, we shall have to notice sundry laboratory experiments which point to the same result as our field observations, and give us an insight into the way in which the transformation has been brought about.

Metamorphic Rocks of Carrara.—The first case that I shall bring forward has been already employed by Sir Charles Lyell, but it is so much to the point that I do not hesitate to reproduce it here.*

On the borders of the Gulf of Spezzia, on the eastern shore of the Gulf of Genoa, there occurs a well-marked threefold group of rocks. The uppermost member is a fossiliferous Limestone with nodules of Flint; below this are Shales; and at the base argillaceous and siliceous Sandstones. These beds are intruded on at various points by eruptive Crystalline rocks, in the neighbourhood of which they become altered and the Limestone converted into white Marble. But besides these local modifications, they are found, when they are followed inland to the heights of the Apennines, to have undergone a more wide-spread metamorphism, and to be at last replaced by a group in which a threefold subdivision can still be traced, but the members of which are of a totally different character to the rocks of the coast section. At the top is the statuary Marble of Carrara; beneath this are rocks known as Talc-schist, Mica-schist with Garnets, and Jaspery Porcellanite; and the lowest member consists of Quartzite and Gneiss, into which an underlying mass of Granite sends veins. The Carrara Marble is a rock of a finely crystalline texture like that of loaf sugar, with little or no trace of bedding, and without fossils, and contains prisms of crystallised Quartz; the Schists and Gneiss are highly crystalline, and possess the structure known as foliation, that is, their crystals are not jumbled together without order, but are arranged more or less in layers, each consisting in large measure of only a single mineral, or they are split up into thin plates, the faces of which are coated by one of their constituents, such as Talc or Mica. The Quartzite and Porcellanite are rocks such as we have already seen are produced by the baking of Sandstones and Shales along the margin of igneous dykes. Now, differing widely as the two ends of the section do, they yet both agree in having a calcareous member at the top, an argillaceous member in the middle, and a siliceous member at the base; and further, when the intervening country is examined, it is found that a passage may be traced by almost insensible gradations from each of the derivative members at one end into the highly crystalline corresponding member at the other end. The Limestone passes step by step into Marble, losing in the change its fossils and its bedding, and having its siliceous nodules converted into crystallised Quartz; the Shales graduate into Schists and Porcellanite; the Sandstones slowly put on the forms of Quartzite and Gneiss.

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* See Bone, Bulletin de la Société Géologique de France, iii. p. 52, for a summary of observation on this district; also Leonhard's Jahrbuch, 1833, p. 102, 1834, p. 563; and Karsten's Archiv., vol. vi. p. 229.

Here, then, is an admirable instance of the gradual passage of rocks of a derivative type into beds possessing the most intensely crystalline structure. If we were suddenly transported from the coast to the mountain sides, we should never suspect any connection between the rocks of the one and those of the other, so totally different are the two from one another; but, by going over the ground between, we

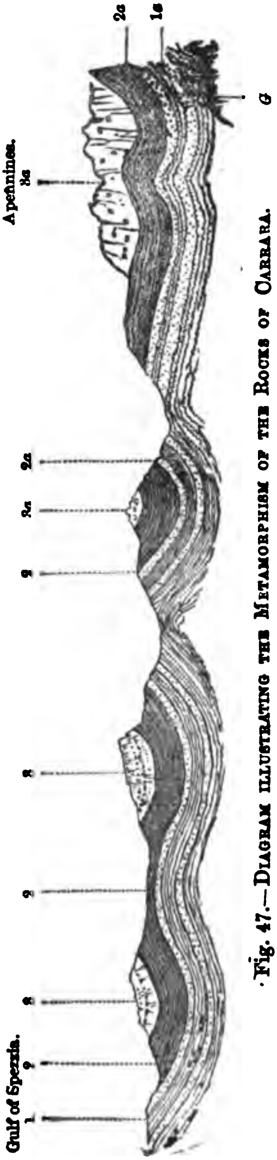

Fig. 47.—Diagram illustrating the Metamorphism of the Rocks of Carrara.

1. Siliceous and argillaceous Sandstones passing into Quartzite and Gneiss (1a), and penetrated by Granite (G). 2. Shales passing into Talcose and Micaceous Schist and Porcellanite (2a). 3. Limestone with Flint nodules passing into Statuary Marble (3a) with crystallised Quartz.

are enabled to detect so gradual a blending of the members of one group into corresponding members in the other, that we become convinced that the beds at one end of the section can be nothing else but the transformed equivalents of those at the other end.

The main facts just described have been thrown into the form of a diagram in Fig. 47. It must not be supposed that this is intended for a geological section of the country; it is only an attempt to bring before the eye in a pictorial form what has just been described in words.

Metamorphic Rocks of County Donegal.—The next instance that I shall lay before the reader is taken from a part of the large tract of Metamorphic rocks in the north-west of Ireland, and is illustrated by the section in Fig. 48.*

On the left we have sandy Limestones (1), and white Sandstones (2), with intrusive masses of Diorite (G). These beds appear to have undergone some, but not a very large, degree of metamorphism. Some of the Limestones are closely grained and semi-crystalline, and among the Sandstones we meet with beds of Quartzite here and there, but the main body of the rock shows feeble signs of alteration. Next comes a thick mass of Quartzite (3), forming the noble hill known as Errigal Mountain; this is an intensely hard, very closely grained rock. crystalline in parts, well jointed, and splintery, very regularly and unmistakeably bedded. That it is a sedimentary Sandstone cannot be doubted, but the amount of alteration necessary to turn any Sandstone into a Quartzite of this nature must have been considerably greater than that which the underlying beds (1) and (2) have suffered. Upon the Quartzite there lies a group of beds (4) consisting mainly of Mica-schist, with interbedded layers of Limestone, Gneiss, and a rock that cannot be distinguished from Granite. The progressive increase of alteration, which occurs in passing from (1) and (2) to (3), becomes still more strongly marked here; the Mica-schist and Gneiss are foliated, the Limestones are all highly crystalline, in some cases converted into statuary Marble, and some of them contain plates of Mica, and some of the Granitic beds are coarsely grained crystalline aggregates. But in spite of the advanced stage of metamorphism through which they have passed, these rocks still retain a most characteristic and strongly marked bedding. In this respect they cannot be distinguished from a group of interbedded Shales, Sandstones, and Limestones; and it is only when we break into them, and become aware of their intensely crystalline texture, that we realise the amount of alteration they must have gone through to reduce them from the condition of ordinary derivative sediment to their present state. As we go towards the right across the group last mentioned, a gradual change becomes apparent; the beds of granitic Gneiss and Granite become thicker and more numerous, and the intervening bands of Mica-schist thinner and fewer, till we at last reach ground where the latter can no longer be detected and which is wholly occupied by Granite. We can here be no longer certain of the existence of bedding, but the rock is traversed by a number of divisional planes ranging parallel to the stratification of the undoubtedly bedded rocks on the left, and the layers, into which the rock is divided by these planes, differ from one another in grain, mineral composition, and other peculiarities, just in the same way as the successive beds of an ordinary stratified derivative deposit are observed to do. Very grave suspicions, therefore, arise in our mind that this apparently amorphous crystalline mass was once a bedded rock, and that the signs of stratification have been all but effaced by the intense degree of metamorphism which it has been subjected to.

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* On the Granites of Donegal, &c., British Assoc. (1863); On the Granite Rocks of Donegal, R. H. Scott; Journal Royal Geol. Soc. of Ireland, i. 144; Geol. Mag., ii. 216, vii. 553.

The section just described offers to our notice a group of rocks

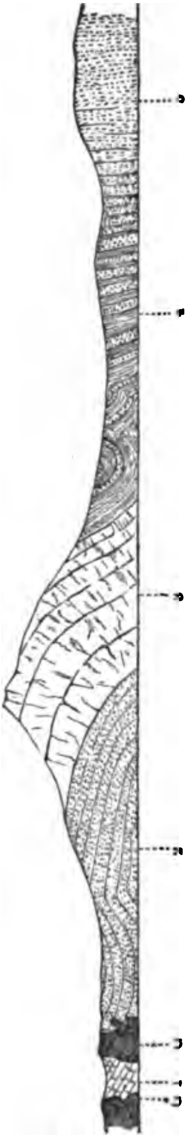

Fig. 48.—SECTION ACROSS THE METAMORPHIC DISTRICT OF ERRIGAL, CO. DONEGAL, IRELAND.
Scale 1½ inches to a mile.

which, in bedding and other characteristics, presents the strongest analogy to derivative deposits, while it differs from these latter in possessing a more or less pronounced crystalline texture. On the first ground we are led to think that the rocks must have been originally derivative, while the impossibility of rocks as crystalline as these are having been formed by derivative methods alone, convinces us that the crystallisation must have supervened after their deposition. And it is in favour of this view that, in proportion as the crystalline texture becomes more and more marked, the traces of bedding become less and less distinct.

It is by a consideration of a large mass of evidence, similar to that furnished by the two cases just given, that geologists are led to a conviction of the metamorphic origin of the rocks now under consideration. Let us summarize the facts just brought before us and the reasoning that flows from them.

In the example of Massa Carrara we start on beds of the ordinary derivative type, and find them, as we follow them across the country, changing by degrees and gradually putting on new forms, till at last they pass into rocks so totally different from those we began with in external look, mineral character, and everything except ultimate chemical composition, that, if we had not been able to trace them continuously from one extreme to the other, and note all the intermediate links, we should never have suspected that the rocks at one end of the section were nothing more than the altered equivalents of those at the other end; but so insensible is the transition, that there cannot be a shadow of a doubt on this point.

In the Irish instance our reasoning takes a different line: there is not the same gradual passage of the same rock from its unaltered to its altered state; the beds are all of them more or less of the same type as those at the Apennine end of the Carrara section. Now, no one can gainsay the conclusion that the latter are altered derivative rocks, and, on the strength of the exact resemblance between the two, we do not hesitate to assert the same of the Irish beds, even though we can nowhere follow them passing into an unaltered state; and this conclusion is further supported by our finding in the greater part of them bedded structure still remaining.

One more fact calls for special notice. In both cases the intensity of the metamorphism keeps increasing, as we go in a certain direction, till the series ends in Granite. It may be that the Granite has been intruded in a fused state, and that heat spreading from it has brought about, in a manner which will be discussed shortly, the metamorphism of the surrounding rocks. But it is equally likely, in many cases far more probable, that the Granite itself is only the result of the extreme stage of metamorphism; that the process, which at certain stages only gave rise to Gneiss, when carried a step further went to the length of actually fusing the rocks it affected, and that the molten mass, cooling under pressure, hardened into Granite. But we shall have more to say on this point in the next chapter.

Effects of Metamorphism.—The most obvious result of metamorphism has been to superinduce a crystalline structure in rocks originally derivative. Its effects upon the bedding vary in different cases; sometimes the stratification can be still distinctly traced, sometimes it has been obscured or replaced by the structure already alluded to as foliation, sometimes neither the original bedding nor foliation are present; if a rock originally contained fossils, these are usually obscured, and frequently altogether effaced, by metamorphism.

Subdivisions of Metamorphic Rocks.—We may conveniently divide the Metamorphic rocks into three classes:—

1st. Those which still retain their bedding.

2nd. Foliated or Schistose rocks.

3rd. Certain Crystalline rocks of the Trappean and Plutonic groups, which are believed by many geologists to be excessively metamorphosed rocks.

About the origin of the first there can be no doubt; their bedded structure, the occasional presence in them of fossils, and the passage that can often be traced from them into the unaltered rock by whose metamorphism they were produced, puts this beyond question. We get an inkling as to the way they were produced by observing that they closely resemble the bands of baked and altered rock, which have been already noticed as frequently surrounding intrusive igneous masses, and by sundry laboratory experiments by which some of them have been produced artificially.

The origin of the Schistose rocks is not quite so evident at first sight. Considered by themselves and judged only by isolated hand specimens, there is little about them to suggest a relationship to the rocks of the first class; but a study of them in the field does occasionally show a passage from them through the latter to unaltered derivative rocks, and leads us to believe that they represent a more advanced stage of metamorphism, in which the rock, without being actually fused, was so far softened and its coherence weakened, that its constituent minerals were free to move among one another and group themselves in separate layers, and, maybe, to become decomposed into their chemical elements, so that the latter were able to enter into new combinations.

There is not much difference of opinion among geologists as to the origin of the rocks which make up the two classes just described; they are generally admitted to be altered derivative deposits. But by no means the same unanimity prevails with respect to many of the rocks which we propose to place in the third class. We shall follow those authors who class as metamorphic certain members of the Trappean and Plutonic groups, such as many Diorites, Compact Felstones, Granites, and Syenites, under the belief that the partial fusion which these rocks have probably undergone has been brought about by the same causes that gave rise to the metamorphism of the rocks of the first two classes, only that in the case of the former the action was more vigorous and was carried further than in the case of the latter. In a word, we shall adopt the opinion that the rocks in question are only intensely metamorphosed products.

But it is only right to state that there are other geologists who will not admit the possibility of these rocks having had a metamorphic origin.

That Trappean and Plutonic rocks have been once in a state of partial fusion is allowed by both sides; the two schools differ in their explanation of the way in which the molten condition was brought about.

In order to make the matter clear, it will be necessary to give a summary of the opposite opinions held on this subject.

There is good reason to believe that the whole earth was once in a state of fusion, and, according to one school, it consists now of an external solid crust, within which a mass or detached masses of the original fluid material still remain in a molten condition. Taking this view of the constitution of our planet, some geologists will have it that all lavas are portions of this molten interior mass, which have been forced up to the surface, and that those rocks known as Trappean or Plutonic, which differ from subaërial lavas in being more compact and crystalline, are portions of the same molten interior mass which have cooled and hardened under pressure. This school, then, draws all igneous products from an internal *permanently molten* reservoir.

But of late years a more careful examination on a large scale in the field of the rocks hitherto classed as Trappean and Plutonic has shown that they can be occasionally traced passing insensibly into foliated, or less highly metamorphosed, or even unaltered derivative rocks; and also that they occur now and then in masses of a bedded aspect among undoubtedly stratified deposits.

These facts have led to the belief that such rocks have not been derived from a molten interior mass, but that they are only intensely altered portions of the solid crust; and when we can trace an ordinary derivative rock becoming gradually crystalline, then putting on foliation but still retaining traces of its bedding and original character, and lastly gradually losing step by step every peculiarity which originally distinguished it and passing into an amorphous crystalline mass, it does seem reasonable to conclude that a chain of results so closely connected with one another are only successive steps of the same process, and that the only difference between the last and the earlier stages is that in the former the process of alteration has been more thoroughly carried out than in the latter. According to this view, then, Plutonic and Trappean rocks have been produced by the melting down of portions of the solid crust, and fusion was produced by a more energetic action of the same causes which gave rise to foliation and other metamorphic changes. And since lavas are only the subaërial forms of Trappean and Plutonic rocks, they also are believed to have arisen in the same manner and from the same cause. By those who take this view rocks, which we would place in a third metamorphic class, are looked upon as the result of a stage of alteration still more advanced than that which gave rise to foliation; they have been more than softened and rearranged—they have been actually reduced in some cases to a state of partial fusion.

Adopting this view of the origin of Trappean and Plutonic masses, we can distinguish two forms under which they occur. They sometimes seem merely to take the place of portions of the surrounding beds without showing any signs of breaking forcibly through them; in other cases they behave intrusively, and send out tongues or dykes into the neighbouring rocks. In the first case a body of the original rock seems to have been quietly melted down or otherwise transformed into a crystalline mass; in the second the action was more energetic—the rock was not merely fused, but expanded during the process of metamorphism, and was by this means forcibly injected into fissures and rents in the surrounding strata.*

The two views as to the origin of molten igneous products are not necessarily antagonistic. They may be both true. Some lavas and traps may have come from an interior permanently fluid reservoir, and some may have been produced by the melting down of portions of the solid crust. On the other hand, the existence of any permanently molten masses near enough to the surface to allow of their contents being forced out into the air, seems on many grounds extremely improbable.

In the preceding pages the words "melted," "fused," "molten" have been repeatedly used. In dealing with lavas we pointed out that, though we might employ for shortness sake these and similar expressions, the reader must carefully bear in mind that they did not necessarily imply perfect or simply igneous fusion. A similar restriction applies in the present instance, for we shall see shortly that water and other agencies aided heat in the production of metamorphism, and that there is no reason to believe that even the most intensely metamorphosed rocks have been more thoroughly melted than ordinary lava.

SECTION II.—DESCRIPTION OF THE PRINCIPAL VARIETIES OF THE METAMORPHIC ROCKS.

We will now notice some of the chief varieties of the Metamorphic rocks.

1st Class.—Those which still retain Traces of Bedding and other Proofs of their originally Derivative Condition.

(*a*) *Siliceous Members.*

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Quartz-rock or Quartzite.—An aggregate of Quartz grains bound together into a very hard compact rock with a splintery fracture. It can scarcely be called a Crystalline rock, but the presence of Quartz crystals in cavities, and occasionally in the body of the rock itself, show that a crystalline texture has been begun to be set up in it, and the grains, when examined through a lens, have a semi-fused aspect. Intermediate varieties occur between the most crystalline form of Quartzite and the more closely grained Sandstones, which lead us to believe that the former is an altered condition of the latter; and this conclusion is confirmed by the following considerations. Blocks of Sandstone, which have been for some time in use for the hearths of furnaces, are converted into Quartzite, and have sometimes a prismatic structure given to them;* and when igneous rocks have burst through Sandstones, a belt of the latter surrounding the intrusive mass is frequently found to be baked into a perfect Quartzite.

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* See Sterry Hunt, Quart. Journ. Geol. Soc. of London, xv. 490.

The typical Quartzites are almost purely siliceous rocks, but varieties occur enclosing crystals of Felspar and other minerals, and one form contains Mica in sufficient abundance, and arranged with sufficient regularity in layers, to give it a schistose structure.

Lydian Stone.—Differs mainly from Quartzite in containing small admixtures of Alumina, Carbon, and Oxide of Iron; the amount of the impurities varies very much in different specimens; often ribboned or laminated. As the more typical Quartzites have arisen from the metamorphism of highly siliceous Sandstones, Lydian Stone would seem to be the result of the alteration of the more impure argillaceous Sandstones and sandy Shales. A case has been already given where Shales have been converted by contact with an igneous dyke into a sort of Lydian Stone.

Innumerable varieties of rocks, to which it is scarcely possible to assign definite names, have arisen from the alteration of impure Sandstones. A very instructive instance is described by Prof. Ramsay in the neighbourhood of Llanberis.† Underneath the well-known roofing Slates of Penrhyn and Llanberis is a group of bands of Slate, Grit, and Conglomerate resting on a mass of quartzose porphyritic Felstone. The Slates, Grits, and Conglomerates are altered for some distance from the junction, "the alteration increasing as it approaches the undoubted Porphyry; and it is easy to note, first, the disappearance of the granular structure in the conglomeratic and sandy matrix, and its gradual assumption of a porphyritic character with small crystals of Felspar embedded, while the enclosed pebbles still retain their distinctive forms; and again, on approaching the recognised Porphyry, the hard outlines of the pebbles in the Conglomerate gradually melt away till they become indistinguishable in the general fusion of the rock. So closely does the matrix of the altered rock resemble the adjoining typical Porphyry in colour, texture, and even porphyrytic character, and by such insensible gradations do they melt into one another, that the suspicion or rather the conviction constantly recurs to the mind that the solid Porphyry itself is nothing but the result of the alteration of the stratified masses carried a stage further into the region of that kind of absolute fusion that in so many regions resulted in the formation of Granites, Syenites, and other rocks commonly called intrusive; and this view is aided by the fact that it is impossible to define any line of demarcation between Conglomerate and Porphyry."

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* De la Beche, Researches in Theoretical Geology, p. 109.

† The Geology of N. Wales (Memoirs of the Geological Survey of England and Wales), pp. 140—145.

Felspathic Sandstones, more or less altered, make up a great part of the Silurian rocks of the southern uplands of Scotland.*

(b) *Argillaceous Members.*

Clay Slate.—This rock may well be placed in the Metamorphic group, though the main alteration that has been produced in it is not so much the development of crystalline texture as hardening and the production of the peculiar structure already described under the name of Cleavage. The different varieties of Clay Slate correspond in mineral and chemical composition with the various forms of argillaceous Shale, and differ only from the latter in their more perfect induration and the possession of cleavage. Both these distinguishing characteristics are due, as we have already seen, to pressure. The cleavage planes of some Clay Slates are flecked over with flakes of Mica, Talc, Chlorite, Chiastolite, and other minerals. In these varieties metamorphism has advanced a step further, and has given rise to an incipient foliation which allies them to the Schistose rocks.

Porcellanite.—The metamorphism of some Clays has given rise to a rock which, from its resemblance to earthenware or china, has received this name. When stained red it is known as Jaspery Porcellanite, or Porcelain Jasper.

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* J. Geikie, Quart. Journ. Geol. Soc. of London, xxii. 513; A. Geikie (Memoirs of the Geological Survey of Scotland), The Geology of East Lothian, The Geology of East Berwickshire, and Explanation of Sheets 3 and 15.

(*c*) *Calcareous Members.*

Crystalline Limestone.—All tolerably pure Limestones seem to have a tendency to assume a crystalline texture. This may be seen, for instance, in many parts of the Carboniferous Limestone of the centre of England, which there is no reason to suppose has ever been subjected to any special metamorphosing influence. The dissolution and precipitation of Carbonate of Lime by percolating water has no doubt much to do with producing this result, but very likely the slow working of molecular change may have aided. With a tendency of this nature, it is no wonder that Limestones, when metamorphic agencies are brought to bear on them, are readily converted into a semi-crystalline or crystalline state. All sorts of varieties occur, some largely and coarsely crystalline, others containing crystals of foreign minerals, such as Mica, Chlorite, Garnet, &c., and some of a beautifully even, closely-grained texture, resembling loaf-sugar, and capable of taking a polish. The last, which are known as Saccharoidal Limestones, furnish the Statuary Marble of commerce. We have already noticed one case in which Limestone of the ordinary derivative type is observed to pass on a large scale into a Crystalline rock; the same change is often noticed where Limestones are invaded by igneous rocks, as, for instance, in the case of the Chalk of the north-east of Ireland.* Crystalline Limestone has also been produced artificially. When Limestone is burnt in the open air the Carbonic Acid is driven off and quicklime remains behind; but Sir James Hall, by confining Limestone in a closed vessel so as to prevent the escape of the Carbonic Acid, and heating it, succeeded in converting it into Statuary Marble.† The experiments were made with Chalk, common Limestone, Marble, Spar, and fish shells. In all cases the Carbonate of Lime, which had been introduced in the state of the finest powder, was agglutinated into a firm mass, possessing a degree of hardness, compactness, and specific gravity nearly approaching to those qualities in a sound Limestone; and some of the results, by their saline fracture, by their semi-transparency, and their susceptibility of a polish, deserved the name of Marble. One specimen, formed from pounded Spar, was so complete as to deceive the workman employed to polish it, who declared that, were the substance a little whiter, the quarry from which it was taken would be of great value if it lay within reach of a market. This last and some others soon crumbled and fell to dust; but many others resisted the air and retained their polish as well as any Marble.

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* Buckland and Conybeare, Transactions Geol. Soc. of London, iii.; De la Beche, Geological Observer, p. 700.

† Edinburgh Phil. Transactions, vol. vi. p. 71.

In some of the micaceous metamorphic Limestones the Mica occurs in sufficient abundance to give them a schistose structure.

Dolomite. — We have seen that some Dolomites and Magnesian Limestones have probably been formed by chemical precipitation, others have undoubtedly been produced by the alteration of Limestone. Such a change is called *dolomitization*. Various views have been held as to the methods by which the metamorphism has been brought about. Arduino in 1779, Heim in 1806, and Von Buch in 1822, suggested that where augitic igneous rocks have burst through or been irrupted below Limestones, magnesian vapour had risen from the fused mass, insinuated itself through the body of the rock, and given rise to dolomitization.[*] This view was stoutly upheld by the last great geologist; and he pointed to the huge dolomitic masses of the Tyrol, below which great bodies of Melaphyre exist, as a case in point. Subsequent examination has shown that the explanation will not hold good in this case;[†] but there is no doubt that Limestones are sometimes dolomitized when they come in contact with magnesian igneous rocks. Bischof quotes a case, mentioned by Coquand, of a Limestone in contact with Basalt, which became more and more magnesian the nearer it approached the latter rock.[‡] But he does not believe the change to be due to the action of vapour, and prefers to account for it by the percolation of water holding Carbonate of Magnesia in solution. The latter salt he believes was obtained by the decomposition of the Silicate of Magnesia of the Basalt by carbonated water, which found its way down between the dyke and the adjoining rock. An experiment of Durocher's is, on the other hand, somewhat in favour of the vapour theory. He heated together fragments of Limestone and Magnesian Chloride in a close vessel, and succeeded in converting part of the former into Dolomite.[§]

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[*] See Naumann, Geognosie, i. 763—765, for details and references.

[†] Fournet, Bull. Soc. Geol. de France, 2nd ser., vi. 506—516; Naumann, Geognosie, i. 768.

[‡] Chemical Geology, iii. 179.

[§] Comptes Rendus, xxiii. 64 (1851).

Even supposing, however, that magnesian vapours have been in some cases the cause of dolomitization, we can hardly suppose that their effect would extend to any great distance from the source which gave them off, and can scarcely apply this explanation to account for the transformation of great masses of Limestone into Dolomite. Another explanation, to which the objection just mentioned does not apply, is that dolomitization was produced by the percolation of water holding Carbonate of Magnesia in solution.*

Professor Harkness has explained in this way the occurrence of Magnesian Limestones among the Carboniferous Limestone of Co. Cork.† They occur under two forms; in some cases they are interstratified with the ordinary Limestone, in others they form vertical ribs, cutting across the bedding like igneous dykes. Wherever the *ribs* occur the rock is well jointed, the walls of each rib being formed by joints; but where *beds* prevail the rock has little or no jointing. In the first case the dolomitising solution found its way most readily down the open vertical fissures, and, spreading into the adjoining rock, altered a band bounded by the joints that gave it passage; where there were no joints, the easiest path was parallel to the planes of bedding through the most permeable strata. Professor Harkness also points out that in some cases the alteration is greater in the upper than in the lower part of the rock, as if the producing cause had been something introduced from above. He supposed the dolomitizing agent to have been the Sulphate of Magnesia and Chloride of Magnesium of sea-water. According to Favre, these substances can alter Limestone into Dolomite only under great pressure, and at a temperature of 200° C., conditions which we can hardly suppose to have been present. It seems more likely, therefore, that it was a solution of Carbonate of Magnesia that worked the change. Ribs of Magnesian Limestone, like those just described, are also met with in the Carboniferous Limestone of Yorkshire, where they are known as "Dun courses." Other cases of Dolomite occurring in ribs will be found in Naumann's

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* Bischoff, Chemical Geology, iii. 164—167, 179; Dana and Jackson, Silliman's Journ. xlv. (1843) 120, 141; Nauch, Poggendorf Ann., lxxv. (1848) 149.

† Quarterly Journal Geological Society, xv. 100; see also Wyley, Journal Dublin Geological Society, vi. 109.

Geognosie, i. 766, 767, with many references to the literature of the subject.

Magnesian Limestones are very frequently full of cavities, and Elie de Beaumont has suggested that these are the result of the decrease in bulk which would accompany the transformation of Limestone into Dolomite, if it were effected by the process we are now considering. The manner of the change was thus. Water holding Carbonate of Magnesia in solution percolated through the rock; the tendency of this salt to unite with Carbonate of Lime caused it to be precipitated, and the carbonated water took up in its place Carbonate of Lime. Out of every pair of atoms of Carbonate of Lime one was removed in solution, and its place taken by an atom of Carbonate of Magnesia. Now—

$$\text{Bulk of two atoms of Carb. of Lime} = \frac{\text{Atomic weight}}{\text{Spec. grav. of Limestone}} = \frac{200}{2.7}$$

$$\text{Bulk of one atom of Carb. of Lime} + \text{one atom of Carb. of Magnesia} = \frac{\text{Atomic weight}}{\text{Spec. grav. of Dolomite}} = \frac{184}{2.85}$$

Whence—

$$\frac{\text{Bulk of resulting Dolomite}}{\text{Bulk of original Limestone}} = \frac{\frac{184}{2.85}}{\frac{200}{2{\cdot}7}} = {\cdot}87158 = 1 - {\cdot}12842$$

So that the shrinking ought to be between 12 and 13 per cent. In some actual cases Elie de Beaumont estimated the cavities at 12.9 per cent. of the whole rock.

The same explanation will apply to the formation of what are known as Potato-stones. These are pebbles which are known by the fossils they contain to have been once Limestone, but which have been converted into Magnesian Limestone. They are hollow inside, and the walls of the cavity are coated with crystals of Bitter Spar. If the alteration was effected by a solution of Carbonate of Magnesia, the consequent shrinking would account for the internal hollow.

A group of rocks belonging to the Permian formation, at Barrowmouth, near Whitehaven, seems to furnish an instance where dolomitization has been brought about by a solution percolating from above downwards. The section is:—

3. Red Marl with lenticular masses of Gypsum.

2. Magnesian Limestone, pebbly in lower part.
1. Breccia, with dolomitic cement in upper part.

The Breccia contains, besides other rocks, many pebbles of Carboniferous Limestone; and in the upper part, where the cement has a dolomitic character, these are frequently converted into Potato-stones. The Limestone, according to Mr. Binney, is one mass of indistinct fossil shells, and contains numerous small hollows filled with Spar; it contains, according to his analysis, about 77 per cent. of Carbonate of Lime and 11·6 per cent. of Carbonate of Magnesia. The abundance of fossils in the rock makes it unlikely that it is one of those Limestones which were formed by precipitation from a solution of calcareous and magnesian salts; it is most likely of organic origin, and was originally an ordinary Limestone. If this be true of the Limestone, it is highly probable that the Breccia contained at the time of its formation no magnesian matter. We may therefore look upon these two rocks as having been originally ordinary marine deposits. But the overlying Red Marl with Gypsum points to a change of conditions. These were probably formed in inland waters, perhaps by some such reaction as Sterry Hunt has suggested, whereby Gypsum and Carbonate of Magnesia were precipitated; the latter was carried down in solution through the underlying beds, slightly dolomitized the Limestone, giving rise to the drusy cavities, and penetrated some way into the Breccia, converting the Limestone pebbles into Potato-stones. The fact that the lower part of the breccia does not appear to be altered seems to show that the water had been robbed of all its magnesian salt before reaching the bottom of the bed.*

Mr. Sorby believes many of the Permian Magnesian Limestones, and also the magnesian portions of the Carboniferous and Devonian Limestones, to be altered Limestones. He says that in thin sections of these rocks fragments of the organic bodies of which they were composed may be sometimes detected, but that frequently the original mechanical structure has been entirely obliterated by the change. He believes the alteration may have been brought about by the infiltration of soluble salts of sea-water, when it had become so far concentrated that Rock Salt was deposited, and that the calcareous salt removed during the change gave rise to accumulations of Gypsum by decomposition with the sulphates of sea-water. Some very solid Dolomites, he remarks, do even now contain about one-fifth per cent. of salts soluble in water, Chlorides of Sodium, Magnesium, Potassium, and Calcium, and Sulphate of Lime, which are doubtless retained in minute "fluid cavities." These must have been produced at the same time as the Dolomite, and caught up from the solution then present, which is thus indicated to have been of a briny character.*

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* For further particulars about these beds, see Binney, Lit. and Phil. Soc. Manchester, 3rd ser., ii. 374; Harkness, Quart. Journ. Geol. Soc., xx. 160.

As a third means of explaining the origin of Dolomite, it has been suggested that water might remove from a Dolomitic Limestone the Carbonate of Lime, leaving the insoluble double carbonate behind. Some organisms do secrete and introduce into their hard parts Carbonate of Magnesia as well as Carbonate of Lime, and it has been hinted that if an organic Limestone was formed of these remains, and the two carbonates became united, the superfluous Carbonate of Lime might be removed, and a Dolomite formed. The highest percentage of Carbonate of Magnesia known to exist in any hard organic structure is 7·644 per cent., and therefore the application of this hypothesis to Limestone formed by animals at all approaching recent forms in this respect is quite inadmissible, on account of the enormous shrinking it would involve.

Besides the Dolomitic rocks already mentioned, there are others interstratified with highly metamorphosed rocks, such as Gneiss and Mica-schist, and containing crystals of Mica, Talc, and Quartz, which we can hardly look upon as anything but the products of alteration. By what means the change has been brought about is as yet uncertain.

In dealing with those Magnesian Limestones which seem to have been formed by precipitation, we were obliged to admit that, though there was good reason to believe that they had a chemical origin, we were still quite in the dark as to the exact nature of the reactions by which they had been produced. Our position is very much the same with regard to the Dolomitic rocks we have just been treating of; there are strong grounds for the opinion that they are altered Limestones, but how exactly the alteration was produced is still an open question.

Gypsum.—We must now say a word about these Gypsums, which have probably been produced by the alteration of other rocks.

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† Reports of British Association, 1856, Transact. of Sections, p. 77.

There can be no doubt that Anhydrite, where it has been exposed to the action of the air or of percolating water, is converted into Gypsum. The process has been observed actually going on, and cases have been observed of masses of Sulphate of Lime which are composed of a coating of Gypsum wrapped over a nucleus of Anhydrite.

Again, Limestone may be, and in many cases probably has been, converted into Gypsum. There are cases known, in the Alps and elsewhere, where a group of rocks contains at some spots great thicknesses of Limestone, while at other spots the corresponding portions of the same group are composed of Gypsum; the Limestone, in fact, is replaced by Gypsum. We can hardly suppose this to have been the original state of things; it seems scarcely possible that marine organic deposits and chemical precipitates could have been formed thus closely side by side; the more reasonable explanation is that the Gypsum is altered Limestone.

The change may have been brought about in various ways. The action of sulphurous acid, which is given off from volcanic sources, would change any Limestone it came in contact with into Gypsum. It is doubtful whether vapour could make its way so thoroughly through the whole rock as to transform large masses; but if converted into Sulphuric Acid it might be carried by water into the very heart of the rock. Sterry Hunt believes that this is the origin of certain masses of Gypsum in the Onodaga Salt Group of Canada; springs are met with, in the district where the Gypsum occurs, containg free Sulphuric Acid, and he thinks that, if this water came in contact with the Limestone of the group, it would form a calcareous sulphate, nearly all of which, on account of its slight solubility, would be deposited in a crystalline form.* He mentions that in one case Mr. Murray observed a slender cylinder of Gypsum running up through several beds of Limestone, and extending in overlying Tertiary Clay.

The conversion of Anhydrite or Limestone into Gypsum is attended by a considerable increase in bulk, and this circumstance has been applied to account for a puzzling occurrence often met with in the neighbourhood of large masses of Gypsum. Around such masses the overlying rocks are tilted up frequently at high angles and bent into an arch, while the rocks below lie perfectly flat. It has been suggested, that, as the original rock swelled during its conversion into Gypsum, it bulged up into a boss and bent upwards the rocks that lay above.* The Canadian Gypsums just mentioned are stated by Sterry Hunt to occur in dome-shaped masses from one to four hundred feet across, the overlying strata are tilted and wrap over the surface of the domes, while the beds underneath are undisturbed; he also says that the ground rises in hillocks above the masses of Gypsum, and that houses are known in some cases to have been gradually raised by the elevation of the surface, and masses of Gypsum have afterwards been found beneath them.†

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* On the Acid Springs and Gypsum Deposits of the Onodaga Salt Group, Silliman's Journ., 2nd ser., viii. 175 (1849). In the Report on the Geology of Canada to 1863 (p. 352), it is stated that the Gypsums of the Onodaga group of Canada "seem to be contemporaneous with the Shales and Dolomites in which they are interstratified, and to have no connection with the springs of the present time." Sterry Hunt, however, maintains there are two Gypsums, one contemporaneous with the rocks among which it occurs, the other now being formed in the manner explained in the text. Silliman's Journ., 2nd ser., xxvii., 365 (1859).

As another possible source of Gypsum, it has been pointed out that in volcanic districts Sulphuretted Hydrogen is given off, and by decomposing Silicates of Lime produces Gypsum and Sulphur.

The theory of the metamorphic origin of Gypsum is, however, as yet in a very rudimentary state. For further hints the reader may refer to Bischof's "Chemical Geology," chap. xix.; Naumann's "Geognosie," i. 760; Zirkel's "Petrologie," i. 268—273; Murchison, Quart. Journ. Geol. Soc., v. 172; Coquand, Bull. de la Soc. Geol. de la France, 2nd series, iv. 124 (1849).

(*d*) *Carbonaceous Members.*

Graphite is the only rock coming under the head sufficiently common to be noticed here.

It consists of Carbon with about five per cent. of impurities, such as Silica, Alumina, and Oxide of Iron.

We have already had occasion to notice Graphite as a constituent or accessory mineral in several rocks. It also occurs in beds and lenticular masses among Schists, Crystalline Limestone, Gneiss, and other metamorphic strata. In general arrangement and microscopic structure these layers of Graphite correspond frequently with Coal and some bituminous deposits, and there is every reason to believe that in many cases Graphite is a highly metamorphosed Anthracite.

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* Elie de Beaumont, Explication de la Carte Geologique de la France, ii. 69, 90.

† Loc. cit. It is difficult to resist the notion that the latter part of the statement comes from some ingenious and kindly Yankee, good at a story, and anxious to give Dr. Hunt a lift.

Just as thick masses of pure Limestone may be looked up as proofs of the existence of animal life at the time of their formation, though no fossils may now be recognisable among them, the probability that Graphite was originally of vegetable origin is so great that its occurrence makes it extremely likely that vegetable life existed during the period represented by the rocks in which it is met with.*

2nd Class.—FOLIATED OR SCHISTOSE ROCKS.

Nature of Foliation.—Foliation, the structure which is the distinctive characteristic of the rocks we have next to consider, is defined by Professor Sedgwick † to be, "a separation of rock masses into crystalline layers of different mineral composition;" and by Mr. D. Forbes ‡ is described as a parallel structure, which "makes its appearance in rock masses owing to the arrangement of certain crystallised minerals in more or less parallel lines, along which the crystals lie on their flat sides or lengthways, *i.e.* having their longer axes in the direction of, and not against, the grain of the rock." The first thing we notice about a foliated rock is a flaky structure or a tendency to split along planes rudely parallel to each other into leaves (folia) or laminæ; and further that this tendency is caused by the presence of roughly parallel layers running through the body of the rock composed in large measure of plates of a single mineral, such as Mica. But these characters alone do not constitute foliation; exactly similar ones are found in some derivative rocks, such as micaceous Sandstone. The distinctive feature of foliated rocks consists in their mineral flakes being *crystallised,* whereas in those derivative rocks which have a deceptive appearance of foliation the mineral plates are worn by attrition.

It is the crystalline character of the constituent minerals, taken along with other peculiarities to be shortly noticed, which leads us to look on foliation as a superinduced structure.

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* Dawson, Quart. Journ. Geol. Soc., xxvi. 112.

† Paper already quoted on "Structure of Large Rock Masses."

‡ Popular Science Review (1870), p. 229. The last clause seems hardly wanted, because it is the arrangement of the crystals that gives the rock its grain.

Degrees of Foliation.—Foliation varies very much in degree. Cleaved Clay Slate often shows an incipient foliation, the planes of cleavage being "coated over with Chlorite and semi-crystalline matter, which not only merely define the planes in question, but strike in parallel flakes through the whole mass of the rock."*

Darwin mentions a case of what looks like arrested developement of foliation in Terra del Fuego. "In several places I was particularly struck with the fact, that the fine laminæ of the Clay Slate, where cutting straight through the bands of stratification, and therefore indisputably true cleavage planes, differed slightly in their greyish and greenish tints of colour, in compactness, and in some laminæ having a more jaspery appearance than others."† Had the process, of which we see in this instance the commencement, been carried on, the result would doubtless have been a foliated rock, with its flakes parallel to what are now planes of cleavage.

From cases, such as those just mentioned, of rudimentary traces of this structure up to the most complete crystallisation and parallel arrangement of the component minerals, all sorts of intermediate gradations exist, and may sometimes be observed melting imperceptibly into one another in the same rock mass, as in the following case observed by Mr. Darwin at the Cape of Good Hope. A mass of Granite has there burst through Clay Slate. "At the distance of a quarter of a mile from the spot where the Granite appears on the beach (though probably the Granite is much nearer under ground) the Clay Slate becomes slightly more compact and crystalline. At a less distance, some of the beds of Clay Slate are of a homogeneous texture, and obscurely striped with different zones of colour, whilst others are obscurely spotted. Within a hundred yards of the first vein of Granite the Clay Slate consists of several varieties—some compact with a tinge of purple, others glistening with numerous minute scales of Mica and imperfectly crystallised Felspar, some obscurely granular, others porphyritic with small elongated spots of a soft white mineral. Close to the Granite the Clay Slate is changed into a dark-coloured laminated rock, having a granular fracture, which is due to imperfect crystals of Felspar coated by minute brilliant scales of Mica." At the actual junction of the Granite and Clay Slate the latter was at one spot "converted into a fine-grained, perfectly characterised Gneiss, composed of yellowish brown granular Felspar, of abundant black brilliant Mica, and of few and thin laminæ of Quartz."* The coloured striping, the micaceous laminæ, and the elongated spots seem to point to an incipient foliation, which reaches its full development in the Gneiss immediately adjoining the Granite.†

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* Sedgwick, Transactions Geol. Soc. of London, iii. 471.

† Geological Observations on South America, p. 155.

What determines the Planes of Foliation.—In some cases it seems highly probable that foliation, even if it does not exactly follow, is closely related to planes of original sedimentary deposition. This appears to be the case with the great mass of schistose rocks that make up the northern highlands of Scotland.‡ The same has been observed to be the case in Anglesea,§ in Arran,‖ in Ireland,¶ in Norway,** and elsewhere. Fig. 49, which is copied from Professor Ramsay's Memoir, shows a case in point. He says, "The beds consist of very hard quartzose grits intermingled with schistose bands, and they seemed partly foliated and partly in lines without clear foliation. In the sandy beds No. 1, marked with dots, I saw no separation of distinct layers of different mineral substances, such as would be called foliation in the sense in which it is used by Mr. Darwin, but only a sort of imperfect separation of material sometimes arranged in wavy lines; while in the schistose beds complete foliation appears, with much twisting of quartzose and micaceous laminæ, each bed, however, still retaining its identity. In No. 2 these contorted laminæ follow the direction of the bed, and in Nos. 3, 4, and 5 they

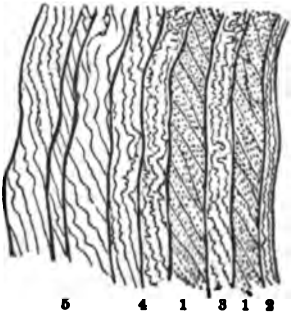

Fig. 49.—FOLIATION PARALLEL TO BEDDING.

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* Geological Observations on Volcanic Islands, pp. 149, 150.

† On the different Stages of Foliation see also Kinahan, Royal Geol. Soc. of Ireland, June, 1870.

‡ Murchison and Geikie, Quart. Journ. of the Geol. Soc. of London, xvii. 171.

§ Ramsay, the Geology of North Wales (Memoirs of the Geol. Survey of England and Wales), pp. 177—188.

‖ Ramsay, Geology of Arran, pp. 88 and 89.

¶ Kinahan, Royal Geological Soc. of Ireland, Jan. 10th, 1866.

** D. Fórbes, Popular Science Review (1870), p. 235.

cross the beds, somewhat in the direction of the lines in the sandy beds, but, eliminating the contortions, at slightly different angles" (pp. 181, 182). In considering this section we must first suppose the foliated laminæ straightened out, because, as we shall shortly see, their crumpling was probably produced subsequently to the foliation. We must also bear in mind that the thicker lines in the figure are unquestionably the edges of bedding planes. In the case of No. 2 the foliation is parallel to these bedding planes, and, therefore, in all likelihood took place over the faces of laminæ of regular and even deposition. In the other cases the foliation crosses the main lines of bedding, but it has a general parallelism to the subordinate layers into which the beds No. 1 are divided, and these latter have a singular resemblance to planes of current lamination. A suspicion, therefore, crosses the mind that here foliation has taken place, as suggested by Mr. Sorby, on planes of current bedding.

The question whether foliation has ever taken place along bedding planes, though much may be said in favour of an affirmative answer, may perhaps be an open one; but the observations of Mr. Darwin and others have demonstrated beyond doubt that in many cases the planes of foliation coincide with those of cleavage. Besides those instances of incipient foliation already given, in which this is the case, Mr. Darwin found in South America immense tracts of intensely metamorphosed Schists, the folia of which had every one of the distinguishing characters of cleavage laminæ: their strike was uniform over large areas and parallel to the leading physical features of the country, and in all cases which he saw, where masses of cleaved and foliated rocks alternate together, the cleavage and foliation were parallel. He sums up the evidence thus: "Seeing, then, that foliated Schists indisputably are sometimes produced by the metamorphosis of homogeneous fissile rocks; seeing that foliation and cleavage are so closely analogous in the several above enumerated respects; seeing that some fissile and almost homogeneous rocks show incipient mineralogical changes along the planes of cleavage, and that other rocks with a fissile structure alternate with and pass into varieties with a foliated structure; I cannot doubt that in most * cases foliation and cleavage are parts

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* I would with deference suggest that for "in most cases" it would be safer to say, "in those cases where such an accumulation of evidence is met with."

of the same process: in cleavage there being only an incipient separation of the constituent minerals, in foliation a much more complete separation and crystallisation."* It is perhaps scarcely the case that cleavage necessarily involves a separation of the constituent minerals, but it is certainly true that if foliation begin in a cleaved rock, the separation follows the planes of cleavage. The coincidence of the planes of cleavage and foliation is, therefore, probably accidental, but it is an accident that will be of very frequent occurrence. In fact this coincidence is so common that it is unnecessary to multiply examples here.

Artificial Production of Cleavage-Foliation.—Coincident cleavage and foliation have been produced artificially by Mr. Sorby and Mr. David Forbes. The first mixed a quantity of scales of Oxide of Iron with Pipe Clay so that they were distributed indiscriminately through the mass. After submitting the mixture to pressure, the scales were found to have arranged themselves in rudely parallel planes perpendicular to the pressure, along which the mass admitted of ready division into thin plates. Mr. Forbes exposed amorphous Soapstone to a moderate heat not exceeding redness for some months, under a pressure of from seven to twelve pounds per square inch, and obtained an aggregate of finely developed crystalline foliæ of a brilliant white or greenish colour, identical with Talc; in fact, a Talcose Schist. Under similar circumstances Clay Slates

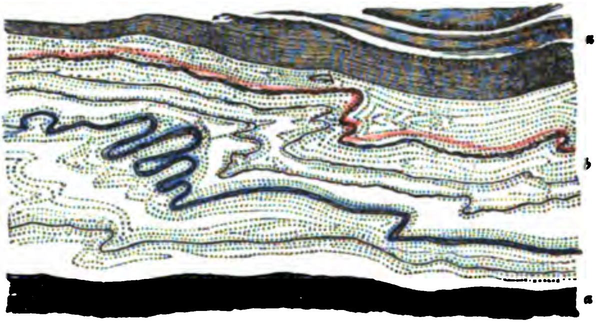

Fig. 50.—Crumpled Laminæ of Foliation.

a. Evenly laminated hornblendic Gneiss.
b. Crystalline Limestone with thin corrugated bands of Gneiss.

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* Geol. Observations in South America, pp. 162 and sequent.

were converted into rocks possessing a beautiful parallel structure, closely resembling Gneiss.*

Crumpled Laminæ.—In highly foliated rocks the laminæ are not plane, but wrinkled and contorted, sometimes gnarled and crumpled to an intense degree. An instance is shown in Fig. 50, copied from one of the "Reports on the Geology of Canada."

Professor Ramsay has given the following explanation of this. Let *ab*, *cd*, *ef*, *gh*, *ik*, in Fig. 51, be the edges of planes of bedding, and the finer lines crossing these the edges of planes of cleavage, and suppose foliation to have been produced over the latter. Then suppose that subsequently the rock mass suffered compression in the direction of the arrows, so that the beds *cdef*, *ghik* become squeezed into the thinner beds *cde′f*, *ghik′*; the planes of cleavage-foliation crossing these beds, having now to pack themselves into a narrower space, must become crumpled up into some such wavy lines as are shown in the figure.

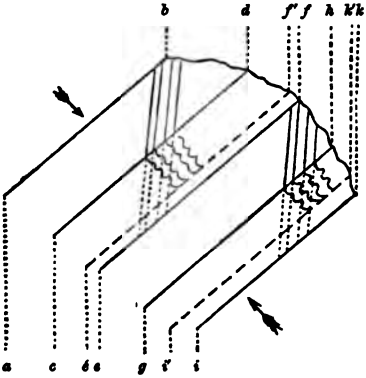

Fig. 51.

Foliation is not confined to the metamorphic representatives of the derivative rocks; igneous rocks, both subaërial and deep-seated, and volcanic ashes and tuffs, where they have been subjected to the necessary conditions, exhibit this structure. Thus a ribboned or banded Trachyte would be eminently suited for its production, or an ash in which induration and cleavage has been brought about by pressure.

Foliation and Ribboned Structure.—Mr. Scrope has some very suggestive remarks ("Volcanoes," pp. 140 and 300) on the analogy between foliation and the banded and ribonned structure, already described, of some trachytic lavas. In the case of these rocks the unequal motion of different parts of a lava stream, as they dragged one over the other, has given rise to a laminated structure in the cooled rock and a platy arrangement of flattened crystals through the mass, and he thinks that just the same result may have been produced in a body of fused Granite forced up under great pressure, and so a foliated Gneiss may have resulted. If the opinion of some continental geologist that some Gneisses are eruptive be well founded, this explanation would account for their foliation; but this cannot have been the origin of this structure in those rocks which have been produced by the metamorphism of sedimentary deposits. As has been already remarked, however, the presence of lamination would be eminently favourable to the production of foliation.

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* See also Daubree, Etudes sur le Métamorphisme, part iii. chap. 10.

Summary.—In the present state of our knowledge it will perhaps not be safe to say more than this on the obscure subject of foliation. That rocks have been subjected to some form of metamorphic action, which has set free their constituent minerals to move among themselves; which has dissolved or melted these minerals, or in some way given them the power of assuming tabular crystalline forms; which perhaps has decomposed them and allowed of the formation of new compounds out of their elements. That the minerals resulting from this action have separated themselves out from the body of the rock, and arranged themselves more or less in distinct parallel layers. That the process of alteration has not been carried far enough to efface those great planes of division, be they bedding or cleavage or any others, by which the rock was traversed when foliation began. That the segregation or separation took place *along those planes which offered the least resistance to the motion of the constituent particles*, or to the passage of those agents which assisted in or produced the foliation; so that if foliation took place in a bedded rock, before cleavage had been produced, the laminæ would have a tendency to be parallel to the bedding; but if cleavage had sealed up the bedding and opened out another set of divisional planes, it would be parallel to those that the foliage would range; in the same way, if the rock contained nodules or concretions, the foliation would be turned out of its way by these and bend round them.*

Description of Foliated Rocks.—After this short sketch of foliation, we will pass on to an account of the principal varieties of foliated rocks.

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* See Prof. Ramsay, Geology of North Wales, *loc. cit.*; Kinahan, Dublin, Quart. Journ. of Science, vi. 185; Royal Geol. Soc. of Ireland, Feb. 8th, 1871, Jan. 10th, 1866.

An almost endless variety of rocks may be classed together as Schists from their possessing the following common character: they consist essentially of Quartz, in which a foliated structure is produced by the presence of parallel layers of some other mineral. Of the type of these we may take Mica Schist, in which the foliation is produced by Mica. Another body of foliated rocks group themselves round Gneiss, which is a schistose mixture of Quartz, Mica, and Felspar, as a typical centre.

The different members of the two groups are connected with one another by numerous intermediate links, and by the gradual introduction of Felspar into its composition the typical form of the first group passes insensibly into that of the second. Transitions are also observed from the first group into less highly metamorphosed rocks, such as Quartzite and Clay Slate; and from the second into rocks which we shall shortly see have undergone a higher degree of metamorphism, such as Granite.

Mica Schist.—Quartz and Mica arranged more or less in alternate layers; the proportion of the two minerals varies almost indefinitely in different instances. The Mica is usually Potash Mica, sometimes Magnesian Mica, sometimes a mixture of both; it forms parallel scales or plates; the Quartz occurs in the form of grains, or, when it is abundant, in large lenticular masses.

Argillaceous Mica Schist (*Phyllite*, *Thonglimmer Schiefer*) is a rock intermediate between normal Mica Schist and Clay Slate, into both of which it passes by insensible gradations, according as the micaceous element becomes pronounced or gradually disappears. It might be termed either an imperfect Mica Schist or a foliated Clay Slate.

Chiastolite Schist.—Argillaceous Mica Schist with crystals of Chiastolite disseminated through it. It is generally found where Clay Slate abuts on igneous rocks, and has been produced by the metamorphising action of the latter on the former. There is a most instructive paper by Professor Fuchs describing the gradual growth by metamorphism of this rock in the Pyrenees, in Leonhard's "Jahrbuch," 1872, p. 878, an abstract of which is given in Chap. VIII.

The presence of an allied mineral, Staurolite, gives rise to *Staurolite Schist;* the reader will do well to consult and compare with the paper just quoted one on the formation of this rock in the *Geological Magazine*, vol. x. p. 102.

Talc Schist and *Chlorite Schist.*—If the Mica in Mica Schist were mixed with or replaced by Talc or Chlorite we should have these rocks. Under their typical form they are usually poor in Silica; sometimes they contain Felspar, and thereby pass into Protogine or Talcose Gneiss.

Some Talcose Schists have been observed to pass laterally into volcanic ash, and are therefore probably the result of the metamorphism of such rocks.*

Calcareous Mica Schist.—Alternate layers of Mica Schist and Carbonate of Lime. It differs from the micaceous crystalline Limestones already mentioned in the presence of Quartz.

Quartz Schist.—When the quartzose element in Mica Schist becomes very large, we obtain this rock, which consists of compact, imperfectly foliated white Quartz, foliated by thin parallel layers of Mica scales. If the Mica disappear, it passes into Quartzite.

Felspathic Mica Schist.—Some Mica Schists contain Felspar, and form a transition between the normal type of that rock and Gneiss.

The presence of accidental minerals gives rise to numerous varieties of the Schists just mentioned, which we cannot describe here.

That Mica Schist is in certain cases a metamorphic rock is clearly proved by its intercalation with rocks so little altered that their derivative character can still be recognised. Thus in the Alps beds of sandy calcareous composition containing fossils are interstratified with Mica Schist. Some Mica Schists can scarcely be distinguished from fissile micaceous Sandstones, and a very moderate degree of metamorphism would be required to convert the one into the other, the foliation coinciding with the original lamination. In other cases Mica Schist has been produced by the metamorphism of Sandstones not necessarily laminated, or sandy Shales, the foliation being a superinduced structure, and the variety depending on the proportions of siliceous and argillaceous elements in the original rock.

In some varieties of Schists the foliation is produced by metallic ores, such as micaceous Sesquioxide of Iron, Zincblende, Iron or Copper Pyrites, Cobalt Ore, &c.

Gneiss.—A schistose aggregate of Felspar, Quartz, and Mica. The Felspar is in crystalline grains, the Quartz in grains or small lenticular discs, and through the mixture formed of these two minerals there run parallel layers or leaves of Mica, giving the rock a foliated structure.

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* Ramsay, Geology of North Wales, p. 45.

The Felspar is usually Orthoclase, but Oligoclase often occurs as well; the Mica is mostly a Potash Mica, sometimes a Magnesian Mica.

Two other minerals, Hornblende and Talc, occur frequently as accessories, and sometimes in such abundance as to give rise to the two following varieties of the rock:—

Hornblendic Gneiss, in which the Mica is in part or wholly replaced by Hornblende. When Hornblende is so abundant as to form the greater part of the rock, it is spoken of as *Hornblende Schist:* this form sometimes loses its schistose character, when it is known as *Hornblende Rock*.

Protogine, or *Talcose Gneiss*, consists of Orthoclase, Oligoclase, Quartz, Mica, and a Talcose mineral; it is sometimes spoken of as a variety of Granite, but the descriptions given of it seem to show that it has always more or less of a schistose structure, and that it is a truly metamorphic rock.

Graphitic Gneiss is a variety in which the Mica is wholly or in part replaced by Graphite. As the latter mineral is probably of vegetable origin, this rock has most likely arisen from the metamorphism of sedimentary deposits containing carbonaceous matter.*

Granulite is a variety of Gneiss containing little Mica, with small garnets disseminated through it. The descriptions of this rock given by different petrologists are somewhat conflicting.

We have mentioned that some Mica Schists contain Felspar, and so show a gradual transition from the normal form of that rock into Gneiss. The latter is also found interbedded with various schistose rocks. This intimate connection between Gneiss and the Schists leads us to look upon the former as having arisen from the more intense metamorphism of some of the highly siliceous members of the same class of rocks as gave rise to the latter. This conclusion is confirmed by the position which Gneiss so frequently occupies among metamorphic rocks. In the two examples of metamorphic districts given at the beginning of this chapter, and in numerous other cases, we have a central mass of some highly crystalline amorphous rock, such as Granite, surrounding this a belt of Gneiss, and outside that a belt of Schist, which gradually shades off into less and less altered beds. The Granite we have seen is either the cause or the extreme form of the metamorphism, and the order in which the surrounding belts of rock occur may well represent the degree of alteration they have undergone, the amount of change decreasing as we recede from the centre when it attained its maximum. Sometimes the passage from foliated Gneiss, through a sort of foliated Granite or Granitic Gneiss, into amorphous Granite, is so gradual that it is impossible to say where one ends and the other begins.

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* See Geological Magazine, iv. 160, for an account of bituminous Gneiss and Mica Schist in Sweden.

Early Theories about Crystalline Schists.—In the early days of geological speculation, the crystalline Schists were not supposed to owe their peculiarities of structure to metamorphism, but were imagined to have been formed all of them at the same time, and pretty much as we see them now, during a very early period of the world's history, when conditions obtained very different from any that now exist. The constituents of these rocks were supposed to have been held in solution in an ocean of boiling water, and to have been precipitated as it cooled. A lurking fondness for this hypothesis seems still to linger in the minds of some eminent geologists. While they are driven by the overwhelming nature of the evidence to admit that there are many cases of schistose rocks which are metamorphosed sedimentary deposits, and that the process which gave rise to them has operated at many different times, they still think it possible, or even likely, that in some of those cases, where there is a very large thickness and extent of crystalline Schists, where no proofs of mechanical origin can be detected in them, and where indications of the existence of life at the time of their formation, either in the shape of fossils or Limestones, are wanting, we may have rocks which owe their crystalline structure, wholly or in part, to chemical precipitation from an ocean, the like of which can have existed only during the passage of the earth from some pre-existing state to its present condition.

We shall see presently that in all likelihood the earth has passed through some such stage as this hypothesis requires, and it may be that during such a period rocks analogous to the crystalline Schists were produced; though, as we have no experience to guide us, we can do no more than form vague conjectures as to what would happen under such conditions; but, assuming that such was the case, there seems no necessity for the opinion that any of the rocks of this class now in existence date from so remote a period.

When we have two masses of Gneiss differing from one another in no essential respect whatever, and when we know that one has been produced by metamorphism, it certainly seems more reasonable to believe that the other was produced in the same way, till some good ground can be shown to the contrary, than to go out of one's way to invent some other purely imaginary method by which it might have been formed. Reasoning from analogy is not necessarily conclusive, but it is safer than reasoning based on dreamy conjecture.

The most telling point against such hypotheses, however, is the fact that the oldest rocks we know, the Laurentian formation of Canada, are crystalline Schists, which are conclusively proved to be metamorphic by the traces they still present of mechanical origin and by the presence in them of what are almost certainly fossils. There may be rocks older than these, but the burden of proof rests with those who assert this to be the case, and proofs have not yet been forthcoming.

3rd Class.—Amorphous Crystalline Rocks.

We have already explained the differences of opinion as to the origin of many of the rocks included in this class, and have pointed out that it is only lately that some geologists have begun to realise that its members may be only intensely altered portions of the strata among which they occur. Among the rocks which come under this head, some Granites occupy a prominent place; and the reasons for holding the above opinion will be more thoroughly brought out when we come to treat of that rock and its allies. We will here give a few instances where there seem good grounds for believing that large masses of amorphous crystalline rock owe their present form to intense metamorphism.

In the district of Carrick, in Ayrshire, there occurs in the midst of a country, composed mainly of hard Felspathic Sandstones with occasional beds of Limestone, a tract of rocks so exactly like intrusive igneous rocks in look and composition and general character, that they were for long referred without hesitation to that class. A careful examination, however, has shown that they have been produced by the metamorphism of the surrounding strata. Mr. James Geikie has traced a gradual passage from unaltered Sandstones, through forms in which an amygdaloidal texture begins to be developed, up to porphyritic and closely grained Felstones, which, judged by look and mineral character alone, could not be distinguished from intrusive members of the Felspathic class of Crystalline rocks; and he has even detected here and there, in the very heart of these apparently intrusive tracts, areas of unaltered rock gradually shading off into the Crystalline rocks which surround them. In other cases the same process, acting probably on beds richer in Magnesia, has given rise to Dioritic rocks which approach quite as closely intrusive rocks of basic composition.*

We meet with rocks which most likely come under the present class in Charnwood Forest in Leicestershire. This tract consists of Clay Slate with associated masses of Syenites, Felstones, and Greenstones. Hand specimens of the three last cannot be distinguished from samples of intrusive rocks of the same composition; but it is quite certain that in the present case these Crystalline rocks have not burst through the beds which surround them, but have been produced by intense alteration of the latter, because they pass by such insensible gradations into the unaltered strata in their neighbourhood, that it is often impossible to trace a boundary between the unchanged and the intensely Crystalline rocks, and in some parts it is possible to observe "every degree of gradation, from a common unaltered slaty character to rocks that seem to be, in hand specimens, igneous, but, on a large scale on the ground, show traces of stratification and other signs proving them to be of sedimentary origin, but so much altered that they have been partly, and in some cases entirely, fused, *and thus pass into so called igneous rocks* of the deep-seated kinds. In Charnwood Forest it would be easy to collect a suite of specimens showing a perfect passage from stratified into igneous rocks."† On the same head another observer remarks: "The general character of the rock is such as to convey irresistibly the impression that it is nothing else but the Clay Slate itself, heated to the melting point, and then crystallised by cooling. It would seem that a series of beds of Clay, more or less pure, were first consolidated into slates, and then subjected, *in situ*, to intense heat under pressure."‡

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* Quart. Journ. Geol. Soc. of London, xxii. 513.

† Ramsay, Descriptive Catalogue of the Rock Specimens in the Museum of Practical Geology, 3rd ed. p. 19.

‡ Outlines of the Geology of Leicestershire, Rev. W. H. Coleman, p. 8.

A very striking instance of a sedimentary rock which has been so far altered as to be indistinguishable from one of intrusive origin is furnished by the deposit called Porphyritic Claystone Conglomerate by Mr. Darwin, which occurs in Patagonia and covers large areas in Chili. Of this he says: "The formation, which I call Porphyritic Conglomerate, is the most important and most developed in Chili. From a great number of sections I find it to be a true coarse Conglomerate or Breccia, which passes by every step, in slow gradations, into a fine Claystone Porphyry; the pebbles and cement becoming porphyritic, till at last all is blended in one compact rock. The Porphyries are exceedingly abundant in this chain, and I feel sure that at least four-fifths of them have been thus produced from sedimentary beds *in situ*. There are also Porphyries, which have been injected from below among the strata, and others ejected, which have flowed in streams; and I could show specimens of this rock, produced by these three methods, which cannot be distinguished."*

A very instructive rock in connection with the present subject is *Halleflinta* or *Felsitic Schist*. It is in character intermediate between Felstone and Gneiss, is foliated or unevenly laminated, and sometimes contains an admixture of Chlorite and occasionally some Mica. It occurs in Sweden interbedded with Gneiss and Granulite, into which it passes insensibly. It is therefore metamorphic, and in all probability is the result of the alteration of beds more early metamorphosed than the surrounding strata; so that while they have been altered only so far as to become Gneiss, it has had a narrow escape of being fused altogether and converted into something indistinguishable from an eruptive Felstone.

A case has been already mentioned in North Wales (p. 271) of a Crystalline rock indistinguishable in many respects from an igneous intrusion, which on the ground presents every appearance of having been formed by metamorphism out of mechanical deposits. Similar examples occur in the Vosges,† and indeed it would not be difficult to assemble a cloud of witnesses far larger than we can find room for here.

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* Letter from Mr. Darwin to Professor Henslow, Dec., 1835. Printed for private distribution among the members of the Cambridge Philosophical Society. For details, see Geological Observations on South America, pp. 148, 149, 169.

† Daubree, Annales des Mines, vol. xxvi.

Serpentine is a rock which may be conveniently described here, because there are varieties of it belonging to all three of the classes into which we have divided the metamorphic rocks. It consists essentially of Silicate of Magnesia with from 12 to 21 per cent. of water. Oxide of Iron very frequently enters into its composition, and the presence of other impurities gives rise to numerous varieties. It is soft but tough, with a soapy unctuous feel, often of a dull green colour, but sometimes beautifully mottled red, green, and purple, with veins of white Soapstone or Asbestos.

as at Lizard P
Cornwall

Serpentine occurs under various forms. It is sometimes distinctly bedded and intercalated among strata of crystalline Schists. Thus in the Laurentian gneissic rocks of Canada it is met with in bedded masses of great purity; it occurs also associated with Limestone or Dolomite, sometimes in grains arranged in bands parallel to the stratification, and sometimes in veins traversing the rock.* In the same country a great thickness of bedded Serpentine also occurs in the Quebec Group of rocks;† and Serpentine has also been found interbedded in thin layers with stratified Diorites at St. Stephen's.‡

In the metamorphic district of Ayrshire, mentioned a few pages back, Serpentines are found along with and passing into metamorphic Diorites, and sometimes closely connected with unaltered Limestones.

The very frequent association of Serpentine with Dolomitic Limestones makes it probable that it has in many cases been produced by the alteration of that class of rocks, and that the process which turned Limestone into Dolomite would, if carried a stage further, give rise to a calcareous Serpentine or Ophicalcite, and then to Serpentine proper.

Where Serpentine and metamorphic Diorites occur together, they may have both arisen from the alteration of rocks rich in Magnesia.

Serpentine is also found with a laminated structure, and when the surfaces of the laminæ are covered by plates of Mica or Chlorite it becomes a foliated rock. Such a rock passes into Talcose Schist, and is perhaps only a metamorphosed form of the latter.

Serpentine also occurs in amorphous masses often of large size, and in veins traversing other rocks. In some of these bosses indistinct wavy lines, parallel to the bedding or foliation of the surrounding rocks, may still be traced, conveying the impression that they are metamorphic masses;* in other cases no structure can be perceived, but even here analogy leads us to infer a metamorphic origin for the rock.

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* See Report of Progress of the Geol. Survey of Canada (1863), pp. 471, 591.

† Ibid., p. 266.

‡ Ibid. (1870, 1871), p. 32.

Veins of Serpentine may have been produced by that extreme form of metamorphism which had caused its products to behave eruptively; it is more likely, however, that they are altered veins of some intrusive Basic rock.

The process by which the rocks mentioned, and probably many others, have been converted into Serpentine, is believed by many geologists to have been a species of pseudomorphism; the original minerals of the rock being gradually replaced by Hydrated Silicate of Magnesia.†

SECTION III.—CAUSES OF METAMORPHISM.

The principal phenomena and products of metamorphism having been now described, it remains to inquire whether we can offer any reasonable explanation of the means by which it has been brought about.

Local Metamorphism by Intrusive Igneous Rocks.—It will no doubt have already occurred to the reader, in connection with this part of the subject, that we often find, along the margin of intrusive masses of igneous rock, that the beds through which they have forced their way are altered into substances identical with some members of the metamorphic class. Sandstones are baked into Quartzites, Limestones put on a crystalline texture, and Shales are converted into Lydian Stone or Porcellanite. The alteration does not extend usually to any great distance, and this sort of metamorphism is therefore spoken of as local (metamorphisme accidentel, de juxtaposition, de la roche encaissante) to distinguish it from the widespread metamorphism (metamorphisme normal, général, régional) which has extended its influence over large areas.

Heat one Agent.—It is clear that in such cases the heat of the molten intrusive rock has had an important share in effecting the change. We are also led to look upon heat as one of the agencies that aided in producing metamorphism, on account of the striking analogies that Metamorphic rocks offer to rocks which we know were produced by igneous fusion, in the character of their crystalline minerals, specially in the presence in them of anhydrous Silicates. Considerations of this nature lead us to look upon heat as essential to the production of metamorphism, in the sense in which we have used the word. And all the successful attempts to imitate experimentally metamorphic processes have required the intervention of heat.

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* Ramsay Geol. of N. Wales, p. 179.

† Bischoff, Chemical Geology, ii. chap. xl.

Heat alone not enough.—But there are a host of reasons why heat alone would not be sufficient. It is not always the case that injections of igneous rocks produce local metamorphism, as would be the case if nothing but heat were wanted for the task. Again, the low conducting power of rocks makes it difficult to understand how heat could have found its way through the vast areas and enormous thicknesses of rock that show throughout a uniform degree of intense metamorphism. Then, we often find crystalline minerals, which must have been generated subsequently to the formation of the rock in which they occur, in rocks the main body of which is very little altered at all. If these were produced by heat, how is it that the heat has had so little effect on the rock surrounding them? On grounds like these we conclude that though metamorphism cannot be produced without heat, something else is wanted.

Heated Vapours.—A study of volcanic phenomena suggests as possible aids heated vapours, such as Sulphurous, Carbonic, Hydrochloric, and Hydrofluoric acids. These we know are given off from lavas, and give rise by chemical reaction to sundry crystalline products.

Water.—Agents like these have doubtless assisted in the work of metamorphism; but there is one substance so universally present in all rocks, and so thoroughly capable of effecting, when in a heated state, so many of the changes which observation shows to have taken place, that we must look upon it as the grand helpmate of heat in bringing about metamorphic changes. That substance is water. We have so few opportunities of becoming acquainted with the portion of the earth below the surface, that it does not readily occur to us how widely water must be diffused throughout the ground beneath our feet, and to what great depths it penetrates. But a little reflection will soon bring home to our minds the conviction that water must exist in as large quantity below as above the surface. In all underground explorations, as the miner knows to his cost, it is met with; and wherever a path is open, it tends steadily downwards. Friction and the narrowing of suitable channels cause a decrease in the amount in many cases as we descend, and sometimes the fortunate presence of a natural means of escape gives rise to what is practically a dry mine, but in all attempts to penetrate below the surface water is the one enemy which we always have to cope with to a greater or less degree. That it descends to depths greater than any we have been able to reach, is rendered highly probable by the existence of thermal springs, which in many cases can obtain their heat only by rising from a very considerable depth. The enormous quantity of water given off during volcanic eruptions also shows that it exists in large quantities at depths below the surface. Even when friction and other impediments counteract the effect of gravity in diffusing water, capillary attraction comes in to entice it through the minute pores and interstices of the rocks, and causes them to be saturated with it. Water again exists in a state of chemical combination in many minerals, and is set free when they are decomposed, as in all probability has happened during the process of metamorphism.

So much for the diffusion of water. We must next take into account the increase of temperature as we descend into the earth. This subject belongs to a subsequent chapter; it will be enough to state here that as we go below the surface the temperature rises, and that the average rate of increase may be taken at 1° Fahrenheit for every 60 feet: at this rate we should, at about a depth of two miles, arrive at the temperature at which water boils at the level of the sea. The pressure at such a depth would probably prevent water from passing into a state of vapour, but in this intensely heated condition, or as superheated steam, it would become a far more powerful agent than at ordinary temperatures, for acting as a solvent, for promoting chemical decomposition, and for softening and diminishing the coherency of the constituent minerals of rocks.

We shall have to notice subsequently that the crumpling and crushing which the rocks have undergone is another possible source of heat, which may well have aided the work of metamorphism at less depths than that mentioned.

Water, too, would not pass down pure; in its passage it would take up the various minerals soluble in it with which it came in contact, and would do this to a larger and larger degree as it became more and more highly heated.*

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* In connection with this see Sterry Hunt, Quart. Journ. Geol. Soc., xv. 488.

Seeing, then, that water is everywhere present, that it is so well able to promote and effect alteration in rocks beneath the surface, and that we know of no other substance that can compare with it in these respects, we are justified in concluding that it must play a leading part in any changes that are being wrought among the rocks of the earth's crust.

Pressure and Depth.—Sundry considerations lead to the conclusion that metamorphism must have gone on at considerable depths below the surface.

A thick coating of overlying rock would be necessary to check the escape of heat, and to prevent the water and other metamorphosing agents, or some of the constituents of the rock, being driven off in a state of vapour; for instance, in the conversion of Limestone into crystalline Marble, we must have pressure to prevent the escape of the Carbonic Acid. It is quite clear, too, that the Crystalline rocks could not have been produced by heat alone at atmospheric pressure, because, if they are fused and allowed to solidify, they harden either into a glass or a stony mass totally different from the original rock; and if they originated from the joint action of heat and water, we shall still require the assistance of depth to raise the latter to the requisite temperature and pressure to prevent it escaping as steam. Further, we have the fact that Metamorphic rocks usually show intense folding and contortion, and it will be explained by-and-by that, as far as we know, this could have been produced only under the pressure due to a thick mass of rock atop. Lastly, the successful attempts to imitate artificially metamorphic processes have all called in the assistance of pressure.*

We must not suppose, however, that metamorphism will necessarily be produced if a rock is sunk deep enough into the earth. There are cases where we can show that rocks have been piled one on the top of the other to a thickness of ten or twelve thousand feet, and yet the bottom beds show no signs of what is usually called metamorphism; on the other hand, we can point to rocks which have not had at the outside half the above thickness of cover on when they were metamorphosed, and are yet converted into crystalline

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* Prof. Geikie has tried to determine the depth at which the metamorphism of the Scotch Highlands was produced; and has shown, that, though it was considerable, it was probably not so great as has been sometimes supposed. (Transactions Edinburgh Geol. Soc., ii. 287.)

Schists. When we reflect how complex the process of metamorphism probably is, and how many causes—heat, water, pressure, and may be others we do not know of—are necessary for its production, the seeming inconsistencies of these cases vanish. We shall also see, by-and-by, that the heat required was possibly not derived directly from the heated interior, but was a result of crumpling and crushing; the mechanical work necessary to produce the complicated puckering of the Metamorphic rocks must have been enormous, and, if this were transformed into heat, it would probably furnish an amount amply sufficient for the work of alteration. If this be so, the amount of metamorphism ought to increase with the contortion, and not necessarily with the depth to which the rocks have been sunk.

We will now glance at some of the attempts to imitate experimentally the process of metamorphism.

Experiments of Daubree.—Among the most instructive are those of Daubree. He enclosed the substances to be operated on along with some water in a glass tube, which was introduced into a strong iron cylinder to prevent its being burst by the expansive force of the steam, subjected the whole to various temperatures, and afterwards allowed it to cool slowly. Among the results obtained were the following. At a dull red heat the action of water alone on the glass of the tube gave rise to numerous well-formed crystals of Quartz and to a Zeolitic Silicate. Obsidian was converted into a substance resembling Trachyte, which, when powdered and examined under the microscope, had all the character of Sanidine or glassy Orthoclase.

In another experiment the mineral waters of Plombières, which are rich in Silicates of Potash and Soda, were substituted for pure water. The walls of the tube were found to be coated with Silica in the form of Quartz crystals and Chalcedony, which appeared to have been derived from the decomposition of the Alcaline Silicates of the water. When a mass of pure Kaolin was treated with these waters, it was converted into a solid substance, confusedly crystallised in small prisms, which proved to be a double Silicate of Alumina and an Alkali with all the characters of Felspar; mixed with this was a little crystallised Quartz. He also succeeded in producing a variety of Augite known as Diopside, and a mineral which there was every reason to believe was Mica. A point of great importance brought out by these experiments was the small quantity of water necessary for the transformations; in some cases this did not amount to a third part by weight of the substance transformed.*

Researches of Sterry Hunt.—Among other experimenters, Dr. Sterry Hunt has pointed out how water holding in solution Alkaline Carbonates and Silicates can, by its action on the heated strata of the Sands, Clays, and earthy Carbonates of sedimentary deposits, give rise to the various siliceous minerals which make up the Crystalline rocks; and he believes that a temperature of 212° Fahrenheit would suffice for the production of Silicates of Lime, Magnesia, and Iron, and that at 480° the Felspathic and Micaceous Silicates generally could be formed.†

Observations of Mr. Sorby.—The researches of Mr. Sorby have thrown great light on the process of metamorphism, and he has shown by a most ingenious line of reasoning that water as well as heat must have taken part in the formation of many Crystalline rocks. It had been long known that crystals often enclose hollow spaces, of all sizes from 1-10,000 of an inch in diameter up to some few large enough to be seen with the naked eye, and that these cavities contain liquid; sometimes the cavities are entirely filled, sometimes there is a bubble in them which moves about like that in a spirit-level; and Mr. Sorby showed that in many cases the fluid is water. Now it is found by experiment that when crystals are formed from solution they contain cavities filled with the fluid from which the crystals were thrown down; that at the time of their formation these cavities are *full* of liquid; that as long as the crystal is kept at the same temperature as that at which it was formed the cavities *remain full;* but that if the crystal cool down to a lower temperature, the consequent contraction of the enclosed fluid *causes a vacuity or bubble to be formed in the cavities.* In crystals formed by simple igneous fusion, such as those which occur in furnace slags, there are cavities, *but they are full of glass or stone*, and, when they contain bubbles, the bubbles do not move.

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* For details of these experiments see Annales des Mines, 5th series, xii. 289; Etudes et Expériences Synthétiques sur le Métamorphisme; Mémoires, Académie des Sciences, xvii. (1860); Bulletin Soc. Géol. de France, 2nd series, xv. 97, xvi. 588. See also Durocher, Etudes sur le Métamorphisme, Bullet. Soc. Géol. de France, 2nd series, iii. 547; Métamorphisme dans les Pyrenées, Ann. des Mines, 3rd series, vi. 78. Delesse, Etudes sur le Métamorphisme des Roches, and Ann. des Mines, 5th series, xii. and xiii. Vernon Harcourt, Report of British Assoc. (1860), p. 175. Mitscherlich sur la Production artificielle des Minéraux crystallisés, Ann. de Chimie, xxiv. 258 (1824).

† Quart. Journ. Geol. Soc. of London, xv. 488; Report on Geological Survey of Canada (1856), p. 479; Silliman's Journal, 2nd series, xxx. 135, xxxvi. 214, and July, 1864.

Now we can by experiment imitate only very imperfectly the conditions under which the minerals of the Crystalline rocks were probably formed; but from the above facts we may infer that, if a fused mass containing water crystallise under pressure sufficient to prevent the escape of the water in the shape of vapour, some crystals might be deposited from solution in the highly heated water and catch up small portions of the fused stone, and so contain glass or stone cavities; other crystals might be formed by crystallisation of the melted stone and catch up portions of the water, and so contain fluid cavities.

Among the numerous instances which Mr. Sorby gives of natural crystals containing water cavities, we may mention, as most nearly connected with the subject now before us, the Quartz and Garnet of Mica Schist and Gneiss. He shows how Felspathic Clays might be converted into crystalline Quartz and Mica, so as to constitute Mica Schist, by the removal of part of the alkaline bases, and argues, from the presence of water cavities, that the alteration was not the effect of dry heat and partial fusion, but was due to highly heated water disseminated through the rock. The fact that the process took place at a high temperature is inferred from the presence of bubbles in the cavities; and by determining the degree to which the crystals must be heated in order to make the liquid expand so as to fill the cavity, he has endeavoured to fix what that temperature actually was. This last step of the problem cannot be solved unless we know also the pressure under which the operation took place; but, by making reasonable assumptions on this head, most instructive results are arrived at.*

Pseudomorphism.—One other action of percolating water has played doubtless an important part in producing metamorphic changes, namely, what is known as pseudomorphic change. By this one or more of the chemical constituents of a mineral is wholly or in part abstracted, and its place taken by a totally different substance, frequently without any modification of the original crystalline form. We have already mentioned Serpentine as a rock which probably owes its present composition to this process, and it has doubtless acted largely in many other cases. For details on the subject, the reader may refer to Bischof's "Chemical Geology."

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* Quart. Journ. Geol. Soc. of London, xiv. 453; Reports of British Association, 1856, p. 78, 1857, p. 92. I hope the short sketch above given will lead the reader to consult these beautiful memoirs themselves. He should also refer to Mr. T. A. Phillip's remarks on the subject. Quart. Journ. Geol. Soc., xxxi. 332.

Variations in amount of Metamorphism.—In considering the action of the various metamorphosing agents we must recollect that they would act unequally on different rocks. Some rocks would conduct heat more readily and be more pervious to water and vapours than others; the final result would also depend on the original composition of the rock operated on; and thus we can easily understand how it is that in a mass of metamorphic rocks we find some beds much more altered than others immediately in contact with them. Thus Professor Geikie tells us that, among the altered rocks of the southern uplands of Scotland, there appears to be always a close connection between the nature and extent of the metamorphism and the chemical constitution of the rocks in which it is manifested. It is always most developed in those strata into whose composition Felspar enters as a main ingredient, while on the other hand in the more quartzose rocks little or comparatively little change has taken place. (Memoirs of the Geological Survey of Scotland, Explanation of sheet 15, par. 35.) New elements besides might well be introduced by water into the rocks through which it finds its way, and we must therefore not be surprised if the chemical composition of a metamorphic rock differs from that of the mechanical deposit from which it was derived.

Subsidiary Metamorphosing Agencies.—The causes mentioned seem, as far as our knowledge goes, to have been the main agents in the production of metamorphism; but in particular instances other subsidiary influences no doubt gave their help. Thus, for instance, Forchhammer believes that the presence of sea-weeds has conduced largely to bring about the present condition of the Alum Slate of Scandinavia.*

Summary.—Our present knowledge does not enable us, and it is doubtful if we ever shall be able, to unravel fully the intricacies of the subtle process of metamorphism; but reasoning, such as that which has been laid before the reader, enables us to form what is probably a very just notion of the general way in which the result has been brought about.

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* Report of British Association, 1844, p. 77.

Heat is an essential requisite, but the difficulty of accounting for the transmission of heat by mere conduction through such vast masses of rock as have been thoroughly metamorphosed, obliges us to look for some vehicle which would propagate it by convection. Such a vehicle we find in water. The universal presence of this substance, and its incessant state of circulation, fit it admirably for the task of acting as a diffuser of heat; and at the same time by its power of softening rocks, and by its chemical reaction, it aids materially in promoting rearrangement of the constituent minerals, decomposition and the formation of new compounds, and the introduction of fresh elements. Other substances, in the state either of liquid or vapour, may have had a share in the process. Lastly, we can obtain the requisite widespread heat, and the means of preventing the escape of water and other volatile substances which aided it, only under the pressure of a considerable thickness of overlying rock; and on this and other grounds we conclude that metamorphism went on deep under ground, and that we see Metamorphic rocks at the surface now only because they have been uplifted, and the covering of rock under which they were once buried has been removed by denudation.

Metamorphism no Proof of Antiquity.—It is a fact which has been long noticed that Metamorphic rocks are more plentiful among the older than among the younger members of the rocks of the earth's crust. So generally true is this, that at one time the fact of a rock being a crystalline Schist was looked upon as conclusive proof of great antiquity.

Such an inference is, however, by no means sound and good. We can point to rocks of this class which have certainly been produced during geological periods comparatively recent; and there can be no doubt that metamorphism has always been going on, and is now in progress. But if we bear in mind the position of the metamorphic workshop, we shall see that the prevalence of metamorphic products among the older rocks is only what is to be expected. The Metamorphic rocks of recent date are, for the most part, hidden from sight, because denudation has not yet had time to strip off the covering of rock beneath which the alteration was effected. It is only in districts like the Alps, where great upheaval and extensive denudation has gone on in comparatively recent times, that we can hope to get a sight of rocks that have been metamorphosed during the later portions of the earth's lifetime. We must also bear in mind that the older a rock is, the greater chance will it have had of having been subjected to metamorphic influence, and this will tend to make metamorphic products more abundant in the older than the newer rocks.

On the other hand, while we are bound to admit that metamorphism has always been going on, we shall see, in Chapter XI., that there is reason to believe that at very remote periods its action must have been more vigorous than at present. Whether, however, any of the Metamorphic rocks formed during these periods still survive, is another and a very open question

CHAPTER VIII.

GRANITIC ROCKS.

> Though there is a great characteristic difference between the Plutonic and Volcanic actions and their products, the two, when looked at largely, are seen so to inosculate, that it is impossible not to refer them to an agency common to both.—R. MALLET.

ONE other group of rocks, namely Granite and its allies, remains to be considered. They form the extreme type of those rocks which were grouped together in the last chapter under the third subdivision of metamorphic products, and they might therefore have been treated of along with other members of that class. We have preferred to give them a chapter to themselves for the following reasons. We are anxious to put clearly before the reader the reasons which have led geologists to believe in the metamorphic origin of many of the so-called Trappean and Plutonic rocks, and the best way to do this seemed to be to work out the argument for one special instance. Now no example can be more suitable for this purpose than Granite, for it was mainly from a study of it that the idea that many so-called igneous rocks are only the result of extreme metamorphism sprang up and gained strength.

Granite, too, forms a connecting link between Derivative rocks on the one hand and subaërial lavas on the other. It can in many cases be observed to pass insensibly into Gneiss, and this in its turn to shade off imperceptibly through Schistose and other less altered rocks into ordinary derivative deposits. On the other hand Granite differs from some subaërial lavas such as Trachyte in nothing but texture; and there can be little doubt that the same melted mass which, when it hardened at the surface, took the form of Trachyte, would, if it had solidified under pressure, have assumed that of Granite.

But while Granite is thus connected with both Derivative and Volcanic rocks, standing as it were half way between them, it yet possesses peculiarities of its own which prevent us from classing it with either, and it may therefore be very conveniently considered by itself.

Difference between Granitic and Volcanic Rocks.—The descriptions already given of the chemical and mineral composition of the Granitic rocks show that in these respects they differ in no essential particulars from some Volcanic rocks. We mentioned, however, that in texture there was a marked distinction between the two classes. This distinction consists mainly in the following circumstance. Granitic rocks are without exception compact throughout; they never show the cellular, slaggy, and cindery textures so characteristic of true Volcanic rocks.

This fact led to the belief that Granitic rocks had hardened from the same semi-molten condition as lavas, but that the cooling had gone on under pressure, and it was pointed out that the necessary pressure would be obtained if we supposed them to have consolidated at some depth below the surface instead of having been poured out in the open air.

Petrological Modes of Occurrence of Granite.—When Granite is studied on a large scale in the field it is found to present itself under three clearly distinguishable forms. It is sometimes bedded or occurs interstratified with undoubtedly bedded deposits; in other cases it assumes the form of an amorphous crystalline mass, which takes the place of a portion of the rocks by which it is surrounded, and gradually melts away into them along its edges; thirdly, we meet with Granite which is marked off by a hard line from the adjoining rocks, which sends veins into them, and is so related to them in lie and position that there can be no doubt that it has burst through them intrusively in a state of fusion.

The first two forms may be distinguished as Metamorphic, the last, provisionally,* as Intrusive Granite.

We will now give a sketch of one of the many cases where a perfect passage can be traced from unaltered sedimentary deposits, through a group of rocks showing a continually increasing degree of metamorphism, till the series ends in Granite; and then go on to describe some instances of the three forms under which that rock occurs.

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* *Provisionally*, because, as we have already pointed out, intrusive rocks are probably only the products of intense metamorphism, and therefore in reality metamorphic.

Granite of the Pyrenees.—An excellent instance of the gradual growth of metamorphism terminating in the production of Granite is found in the Pyrenees, and has been most carefully worked out by Professor Fuchs.*

In that mountain chain there are several detached masses of Granite, and around each of these there wraps a belt of altered rocks, the metamorphism of which begins at the edge farthest from the Granite in traces which can be detected only by the most careful scrutiny, and in a general way increases as the Granite is approached. The following are the principal steps in the gradual series of changes.

Outside the zone where metamorphism first becomes apparent there is Clay Slate, which to the naked eye and even under a pocket lens seems perfectly homogeneous; magnified 400 times certain dark points, indistinctly outlined, make their appearance, and under a power of 900 the rock resolves itself into an interlacing network of fine crystals of Quartz, Mica, Chlorite, and a little Magnetite. Next to this rock comes a Clay Slate in which the dark spots become more readily distinguishable, but even here they are so small that they would not be noticed with the eye alone, were it not that their dull colour contrasts with the lustrous brilliancy of the rest of the rock; when this rock is highly magnified, the little spots are seen to be concretions, and Quartz and Mica are clearly distinguishable in the body of the rock. As we get further into the metamorphic zone the small concretions increase in size, and become more distinctly outlined, till the rock becomes a true Nodular Schist (Knotenschiefer or Fruchtschiefer), at the same time the Quartz and Mica are more distinctly developed, so that the rock passes into a form intermediate between Clay Slate and Mica Schist to which it is not possible to assign a definite name. The concretions continue to increase in number and size, till they at last assume the form of dark prismatic bodies, which are crystals of a mineral known as Andalusite.

As we advance still further into the heart of the metamorphic region, the rock assumes more and more the form of a mixture of Quartz and Mica, and a curious change is noticed in the concretions and Andalusite crystals: their outline becomes indistinct, Mica makes its appearance in them, and at last they fade gradually away and are replaced by the latter mineral; in fact they undergo the process of change known as pseudomorphism, and Mica is gradually substituted for Andalusite. The rock thus passes into a typical Mica Schist. As soon as the change has been effected Felspar begins to make its appearance, at first sparingly, so that it is no more than an accidental constituent, but it becomes step by step more plentiful, till the Mica Schist at last puts on the form of a foliated compound of Quartz, Mica, and Felspar, that is, passes into Gneiss; and in many cases it is impossible to say where one rock ends and the other begins.

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* Die Alten Sediment-Formationen und ihre Metamorphose in den französischen Pyrenäen, von Hern Professor C. W. C. Fuchs; Leonhard's Jahrbuch, 1870, pp. 717, 851. See also Verhandlungen der k. k. Geologischen Reichsanstalt, 1869, p. 314.

The earliest appearances of Gneiss are finely grained and poor in Quartz, but as we approach the Granite the rock becomes coarser and the Quartz more plentiful.

Lastly the Gneiss loses by degrees its Schistose structure, and passes by the most imperceptible gradations into true Granite; some of the intermediate varieties, which partake in a manner of the characters of both rocks, have been called Granitic Gneiss.*

As a rule the degree of alteration increases steadily as we approach the Granite, but this is not universally the case. Occasionally beds actually in contact with Granite are less highly altered than others farther off. In such cases the amount of metamorphism has probably been determined by something in the original constitution of the rock, which has caused some beds to be more easily metamorphosed than others.

Metamorphic Granite.—We will now give one or two instances of those modes of occurrence of Granite which have been distinguished as metamorphic.

We can, as has been said, distinguish two forms of this rock. The first, where a truly Granitic rock has been produced, still retaining traces of the original bedding: such Granites differ from Gneiss only in the absence or scanty appearance of foliation. In the second form, the metamorphic influences seem to have been powerful enough to efface the bedding, and the result has been a crystalline amorphous mass which replaces a portion of the rocks that surround it, but shows no signs of having burst violently through them. Hand specimens of such rocks could give us no clue to the way in which they arose; but a study of such masses in the field proves them to be encircled by belts of strata, each of which shows, as we proceed outwards, a smaller and smaller degree of alteration till we at last reach rocks perfectly unchanged; and these belts are not separated from one another by hard lines, but each melts imperceptibly into the one on each side of it.

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* There is a belt of metamorphic rock around the Granites of Skiddaw and Carrock Fell in Cumberland to which the above description would apply almost word for word.

The rocks characterizing the first form would seem to have been produced by metamorphic action exerted uniformly over large areas. In most of the cases belonging to the second form there seems to have been a centre where the energy of metamorphism attained a maximum, and from which it gradually decreased in all directions.

The distinction between the two cases may be illustrated by the following example. If heat be supplied uniformly to the under surface of a thick metal plate—if, for instance, it form the lid of a vessel of boiling water—temperature of the upper surface will be the same all over; but if we direct a jet of flame against the back of the plate, there will be on the front a point of maximum heating, from which the temperature will decrease all round.

Donegal.—One instance of Granite which seems to come under the first head has been already given in the description of the metamorphic district of Donegal (p. 264), where true beds of a rock, indistinguishable from Granite, occur interstratified with Mica Schist and other metamorphic rocks, and where these alternations of Granite with other rocks pass gradually into a large mass composed entirely of Granite, which possesses what may be traces of an originally bedded structure.

Brittany.—What seem to be Granites of a similar origin are met with in Brittany. In that province two very distinct forms of Granite occur. One forms the flanks of the hill ranges. It is finely grained, and contains interstratified beds of Mica Schist, Common Gneiss, Granitic and Talcose Gneiss, into which it passes so insensibly that it is impossible to define a boundary between the two. On the borders of the Granitic areas the Granite is flanked by Gneiss, into which it passes imperceptibly, and the latter shades off through Mica Schist into broad tracts of Clay Slate. As we approach the Granite, crystals of a mineral known as Staurolite begin to make their appearance, and become more plentiful and more perfectly formed the nearer we get to that rock. All these indications seem capable of explanation only on the supposition that the Granite is a truly bedded rock, which has assumed its present form through metamorphic action. Whether the result of this action has ended in the production of Granite or some other form of altered rock, would depend partly on its intensity and partly on the composition of the rock submitted to its influence. Where we get beds of Granite interstratified with other rocks, the former were probably strata whose composition rendered them more susceptible of metamorphism than the latter. Large tracts of Granite may have arisen from the alteration of a great thickness of such rocks, or from an intensity of metamorphism sufficient to convert into Granite rocks of different mineral composition.

That the extent of metamorphism does actually depend in some measure on the composition of the rock operated on is found to be the case in many instances, of which the following may be taken as an example. In speaking of some metamorphosed beds in the southern uplands of Scotland, Professor Geikie states that the character and extent of the metamorphism have been largely determined by the original composition of the rock. Its Quartz grains have suffered little or no change; it is the dark argillaceous base or matrix that has undergone metamorphism. Hence, when a coarse quartzose grit occurs it has suffered little alteration; but where, on the other hand, the rock has been formed out of a fine sandy Silt or muddy Sand, the metamorphism reaches its maximum. (Memoirs of the Geological Survey of Scotland. Explanation of sheet 3, par. 25.)

The other Granite of Brittany is more coarsely grained than the one just described and porphyritic. It does not show intercalations of other rocks; it penetrates and sends veins into the first, and contains fragments of Gneiss. These facts show that this Granite has been forcibly thrust in among the group of beds of which the first Granite is a member. This Granite forms the peaks and summits of the hill ranges.*

Priestlaw.—Of the second form under which Granite occurs, no better instance can be found than that of Priestlaw in Berwickshire.† This is a triangular mass, about one square mile in extent, surrounded on all sides by Felspathic Sandstones and Shales. The rock of which it is composed varies in texture and grain, but is for the most part a well-marked Granite, made up of Felspar, Quartz, and Mica, with occasional Hornblende. Professor A. Geikie has described with great care a section, which starts about a mile from the hill, and shows a series of gradual changes in the surrounding beds, which terminate in Granite.

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* Explication de la Carte Geologique de la France, i. 192; Geol. Mag., x. p. 102.

† Playfair, Illustrations, Works (1822), i. 328; The Geology of East Lothian (Memoirs of the Geological Survey of Scotland), p. 15. For another similar instance, see the Geology of North Berwickshire. p. 29.

He notes first that the strata become exceedingly fine-grained and compact, ringing with a metallic sound when struck; the Sandstones, however, still retain a granular texture, and the Shales, even when almost converted into Jasper, still show their fissile structure along a weathered face. The next change noticed is the appearance of a number of veins, beds, or dykes of rock indistinguishable from Felstone. These are not, as might be supposed, intrusive masses, they shade off so imperceptibly into the Sandstone adjoining them, that they are evidently metamorphosed portions of the latter. One of these crystalline beds has a base of pink crystalline Felspar, with scattered specks of black Mica and Hornblende; in another case, a bed of exceedingly hard Sandstone contains granules of dark vitreous Quartz, and is so extremely altered that it might readily pass for a Felstone, were it not that its bedded structure is still distinct. The number of these crystalline masses and the intensity of the alteration continues to increase, till we at last reach rocks of which it is hard to say whether they are to be called Sandstones or Felstones; then follows a rock with much of the character of a Sandstone, but which soon passes into an undoubted salmon-coloured Felstone; this becomes again more finely crystalline, until it once more resembles Sandstone. It is here composed of Felspar, Quartz, and Hornblende, with Mica. To this compound immediately succeeds by a rapid increase in the size of the crystals the true Granite of Priestlaw.

This section shows beyond doubt that the Granite occupies a centre from which metamorphic action extended itself around among the adjoining rocks. The question arises, is the Granite itself only the final step in the series of changes by which the surrounding beds have been rendered more and more crystalline; or is it a mass, intruded in a molten state, from which heat has spread outwards, and brought about these changes? There is much against the latter view. The alteration produced by intrusive igneous masses seldom extends so far as in the present case into the adjoining rocks. But what tells most strongly against the second explanation is the almost insensible gradations by which the passage is effected from slightly altered Sandstones and Shales into Granite.

An intrusive mass would probably produce some alteration of the surrounding rocks; but there would still be a line of demarcation between the irruptive and the altered rocks unless the latter had been converted along its inner margin into a substance exactly identical with the former. This is not a thing very likely to happen, but it is only in this way that the gradual melting away of the more highly crystalline into the less altered rocks could be made as perfect as it is in the present instance.

A case like this, then, shows, that *Granite can be produced by the metamorphism of rocks in situ*, for some at least of the Priestlaw Granite must have originated in this way. Thus much we must admit; and if we admit this, there is no ground for refusing to believe that the whole could have been formed in the same manner.

South-west of Scotland.—Mr. J. Geikie has described some Granites in the south-west of Scotland, which seem to have had a similar origin to that of Priestlaw. The mass of the country is composed of Felspathic Sandstones interbanded with occasional beds and broad belts of Shales and Mudstones. The former approach Granite in composition more nearly than the latter, and we might therefore expect that, if a group of alternations of such beds became converted into Granite, the transformation would be carried to a larger extent in the Sandstones than in the Shales. This is found to be the case. There are certain patches of Granite to the north-east of Loch Doon, which make their appearance in broad bands of vertical Felspathic Sandstones flanked on either side by hard flinty Shales. The Shales are finely crystalline along their line of junction with the Granite, but the metamorphism quickly ceases as we recede from the Granite along the trend of a belt of Shale; on the other hand, when we proceed along a band of the Sandstone we find alteration extending to a much greater distance. Where the hard slaty Shales impinge on the Granite, we have no difficulty in laying our finger upon the line which separates one rock from the other; but at the point where the Granite and the Sandstones come together, the union of the two rocks is so intimate, that we have usually no line of demarcation, but, on the contrary, a gradual passage.*

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* Geological Magazine, iii. 529.

The same author, in describing a similar tract of Granite and Minette in the same neighbourhood, which he believes owe their present form to metamorphic action, says: "The metamorphism of these rocks has been deduced from a variety of considerations. The chemical composition of the unaltered strata and the Crystalline rocks is similar, and distinct passages can be traced from granular and slightly altered Felspathic Sandstones through masses of various textures (the main constituent being Felspar, with Quartz and Mica more or less abundant in places) into Crystalline rocks, such as Minette and Granite. When the relation of these crystalline masses to the surrounding unaltered Sandstones is considered, the metamorphic character of the former becomes still more apparent. The Sandstones are not broken through and violently displaced, nor is there any appearance of confusion, as the centres of greater metamorphism are approached. On the contrary, the dip and strike of the strata continue unchanged and perfectly distinct until the rocks begin to assume a 'baked' and semi-crystalline texture, and the bedding gradually becomes obscure, and at last vanishes altogether. But after the metamorphic area is traversed, and the unaltered strata on the farther side are reached, the Felspathic Sandstones again appear with exactly the same dip and strike, giving no evidence of disruption by great masses of igneous rock. It seems reasonable to conclude, therefore, that the Felspathic Sandstones were once continuous across the area now occupied by Crystalline rocks, and that these Crystalline rocks have not been erupted from below, but are in truth only the Felspathic Sandstones under a different form. The Sandstones in this area have been simply metamorphosed into Crystalline rocks: they have changed their texture while retaining the same general composition."*

Intrusive Granite of Devon and Cornwall.—We next pass on to some cases in which the relation of Granite in lie and position to the surrounding rocks, and its behaviour in other respects, can be explained only on the hypothesis that it has been forcibly intruded into the rocks that now surround it.† The great bosses of Granite that occur in Devonshire and Cornwall seem to be of this nature, the evidence on a large scale being perhaps most conclusive in the case of that one which forms Dartmoor.

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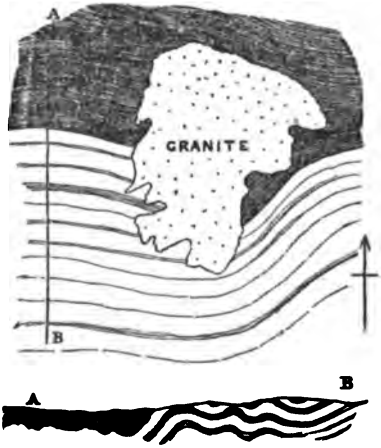
* Memoirs of the Geol. Survey of Scotland. Explanation of sheet 22, par. 10.

† The term *irruptive* is often applied to deep-seated intrusive rocks, to denote that they have burst through the surrounding strata without necessarily reaching the surface; while those intrusive rocks which have been

The surrounding country, the general structure of which is shown in Fig. 52, contains two very distinct groups of rocks. The upper, shown by the darker tint, consists of Sandstones and Shales, often with much carbonaceous matter, and here and there beds of impure Anthracite. Some earthy Limestones occur among the lower beds. The underlying group is made up of Clay Slates and hard Grits. Both groups are thrown into a number of complicated folds and undulations, but in spite of these have a general dip to the north, as shown in the section, so that their separate beds come out to the surface in lines trending on the whole east and west. Now it will be noted that one boundary of the Granite runs nearly due north and south, or directly across the bedding, and this could only happen in one of two ways. Either the Granite is an intruded mass, or it is a portion of the surrounding rocks which has been melted down, and on cooling has assumed the form of Granite.



Section along the line A B.

Fig. 52.—Geological Sketch-map of Dartmoor.

There are many reasons for not entertaining the latter supposition. If this were the true explanation, we should expect to find the Granite showing a passage into the adjoining rocks, losing by degrees its crystallisation and

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discharged from subaërial vents are spoken of as *eruptive*. The latter are the igneous rocks of Delesse; the former are included under his pseudo-igneous and non-igneous classes, in the formation of which other agents, besides heat, such as pressure, water, and molecular action, were concerned. The names are not very happy, for the last-named agencies have also had a share in the production of rocks of his igneous class.

gradually assuming a granular texture and bedded structure; but such is not the case, it is clearly marked off from the rocks with which it comes in contact. Further, if the Granite had been produced by the melting of the surrounding rocks, it would seem likely that the fusion of two such different groups as they are composed of would have given rise to products of different form and composition, and that we should have found one kind of Granite prevailing on the north and another on the south of the area; but this is not the case, the Dartmoor rock is singularly uniform in character throughout.

Considerations like these, combined with the marked way in which the Granite cuts across the bedding, lead us to conclude that this rock has not been derived by any modification of those which surround it, but has risen a perfectly independent mass from below, and forced its way through them.

And this conclusion is further confirmed by several minor points in the behaviour of the rock. Though the line of separation between Granite and the adjoining rock is sharp and distinct, the latter has often undergone just the same sort of baking and alteration as we have already seen occurs along the margins of intrusive dykes. The Granite also sends veins into the rock in contact with it, and has caught up and enclosed in itself portions of the beds which it penetrates.

All the evidence, therefore, leads us to the conviction that this is a body of rock which has been forcibly intruded in a molten state, and similar reasoning leads us to a like conclusion with regard to the other Granitic bosses which occur between Dartmoor and the Land's End. The probability is, that beneath the whole of this district there stretches a sheet of Granite; that this was once in a state of fusion, and was then buried under a much greater thickness of bedded rocks than at present, and every here and there bosses, projecting above the general surface of the mass, were thrust up into the overlying covering; that denudation has stripped off enough of the capping to expose the summits of these bosses, but has not worked its way down to the spread of Granite beneath from which they all spring.*

Intrusive Granite of Brittany.—We have already noticed the occurrence of two kinds of Granite in Brittany, one intrusive, and the other apparently truly interbedded with Metamorphic rocks. The first forms the peaks and ridges, and the second is found along the flanks of the hill ranges. This restriction of each kind to a separate region seems full of meaning, for before the rocks were brought into their present position, the beds out of which the first Granite was formed were the lowest of the group, while those which gave rise to the second Granite were higher up in the series.* The metamorphism of the first Granite therefore went on at a greater depth than that of the second, and was proportionably more intense, so that the rock came not only to be fused but to be driven forcibly into the strata around it; while the second Granite having been formed at a smaller depth, when the metamorphism was less complete, still retains traces of its original bedding.

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* For a description of another area of intrusive Granite, see Jukes's Manual of Geology, 3rd ed., pp. 241—245.

Granite Veins.—In the cases just described among the facts tending to establish the intrusive behaviour of the Granite were the sending of veins into the adjoining strata, the occurrence of included blocks, and contact-metamorphism. We will now give a few further illustrations of these occurrences.

It was from the observation of veins proceeding from a Granite mass and penetrating the overlying rock that Hutton was led to assign an igneous origin to Granite.† In some cases perhaps the appearance of veins may be deceptive; what look like veins may sometimes be seen proceeding from a Granite, which there is good reason to think has never been completely fused; these, it may be, are portions of the adjacent rock, which yielded more readily to metamorphic influence than the more stubborn body of the rock itself, and so became converted into granite, while the rest of the rock remained comparatively unaltered. But such an explanation is not admissible in those cases where Granite veins traverse rocks, such as Limestone, which no amount of metamorphism could convert into Granite. Of many such instances we may take the following as an illustration. The strata in the region between the Massawippe River and Canaan, in Canada, are in many places pierced by considerable masses of a beautiful Granite, which consists of white Quartz and Felspar, with a rather sparing amount of Mica uniformly mixed. Its intrusive nature is clearly shown by the

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* The student will realise this better when he has gone through Chapter IX.

† Playfair's Illustrations, Works, 1822, vol. i. pp. 101, 308.

Granite dykes, which proceed from it in various directions. One of the largest masses measures about six square miles; it appears to displace the calcareous strata which it penetrates, as these are observed to dip from it in several places. At one spot, within a short distance of the edge of the granitic nucleus, a great number of Granite dykes are seen, cutting the basset edges of the Limestone beds, the whole having been worn down to a horizontal surface, a portion of which is represented in Fig. 53. Some of the main dykes are from two to three feet in breadth, and divide into a multitude of irregular and reticulating branches, many of which are not more than the eighth of an inch wide. In the face of an escarpment, which rises from the Granite nucleus to this horizontal surface, a large dyke, of which all the others are probably ramifications, can be traced down to its source.*

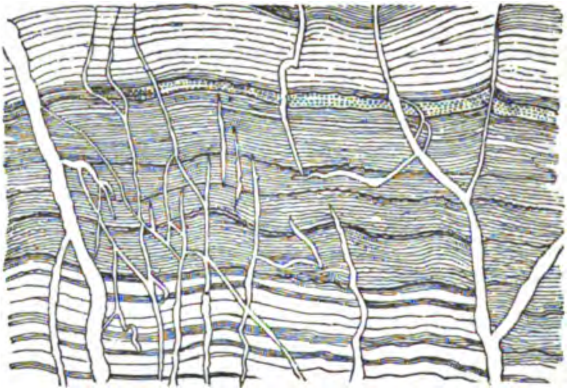

Fig. 53.—Dykes of Granite cutting through Limestone.
Scale, about 1—500th.

Good illustrations of Granite veins will be found in Plate V, and on pp. 168—187 of De la Beche's "Report on the Geology of Cornwall, Devon, and West Somerset;" and in Professor Ramsay's "Geology of the Island of Arran."

Included Blocks in Granite.—Those masses of Granite which appear to have behaved intrusively, often enclose fragments apparently torn off from the rocks through which they have forced their way, and these blocks frequently show an external baked, or otherwise altered, coating. The reader will recollect that the same thing is often observed in the case of dykes and other intrusive igneous masses. The following is one out of many such cases. In the Pyrenees is a Granite containing many blocks of a dark blue Limestone, identical with a rock found in the neighbourhood. The outside crust of these fragments is converted into White Marble, the crystalline texture gradually disappears towards the interior, and the centre has the same colour as the rock from which they were derived.

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* Report on the Geol. Survey of Canada up to 1863, p. 434.

It does not necessarily follow that all included masses of foreign rock which are met with in Granite have come there in the way just described. When Granite has arisen from the intense metamorphism of a group of rocks, some beds of which were more susceptible of metamorphic influence than others, it may well happen that portions of the less easily metamorphosed beds may remain comparatively unchanged in the middle of the crystalline mass, which resulted from the reduction of the more readily altered strata. Cases of this sort have been noticed among the Granites of the south of Scotland by Mr. J. Geikie, see p. 313, and *Geological Magazine*, iii. 533.

Instances have been described of included masses of enormous size in Granite.* One cannot help suspecting that in such cases we are dealing with a metamorphosed group of beds of variable composition; that some have been converted into Granite, while others were better able to resist alteration; and that the supposed included masses are really portions of the latter, rocks in fact that remained unaltered while the beds on either side of them were altered so as to put on a granitic form.

Contact-Metamorphism by Granite.—We have already seen how rocks in contact with intrusive igneous masses are frequently baked, hardened, and otherwise altered for a short distance from the plane of junction: just the same effect has been produced in the neighbourhood of Granite masses.

Thus at Grange Irish, in the Carlingford Mountains, in Ireland, a fine grained Hornblendic Granite sends veins into beds of overlying Limestone: the Limestone is converted into a bluish sugary marble containing garnets. Here, too, the Limestone has reacted on the Granite itself, and wrought a singular change in its composition.

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* Zirkel, Petrographie, i. 503.

Professor Haughton gives the following results of his analysis of the Granite ten yards from the point where it comes in contact with the Limestone:—

		Equivalent to	
Silica	71·41		
Alumina	12·64		
Protoxide of Iron	4·76	Quartz	17·16 per cent.
Lime	1·80	Potash Felspar	67·18 „
Magnesia	0·63	Hornblende	15·40 „
Potash	5·47		
Soda	3·03		

The dykes which proceed from this rock and penetrate the Limestone are found to have the following composition:—

		Equivalent to	
Silica	47·52		
Alumina	28·56		
Protoxide of Iron	7·23	Anorthite or	
Lime	15·44	Lime Felspar.	85·84 per cent.
Magnesia	1·48	Hornblende	14·16 „

Comparing these two analyses we see that "the quantity of Hornblende remains almost unaltered, and that the effect of the addition of Limestone to the melted Granite has been to convert the Quartz and Orthoclase into Anorthite. In this operation the alkalies of the Orthoclase have disappeared; the Lime, being a more fixed base at high temperature, has altogether displaced the alkalies."*

The change of Limestone into crystalline Marble by intruded masses of Hornblendic Granite in the Island of Skye has been described by Professor Geikie.† Under similar circumstances Clay Slates and Sandstones have been converted into Micaceous Schists, Gneiss, or similar foliated rocks.

We must recollect that contact-metamorphism is not in itself a proof that the Granite in whose neighbourhood it occurs was necessarily intrusive. Alteration around a mass of Granite will occur, when the latter has been produced by the melting down of rocks *in situ*, without the process having gone far enough to give rise to intrusive behaviour. But in the latter case there will be a gradual transition from Granite, through less highly altered rocks, to beds quite unchanged: where Granite has behaved intrusively, there will be a more or less marked line of demarcation between it and the rock it invades.

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* Quart. Journ. Geol. Soc., xii. 192—198.

† Ditto, xiv. 18.

The Origin of Plutonic and Trappean Rocks.—It is on facts such as those just described that we must base our speculations as to the origin of Granite and of the Trappean and Plutonic rocks in general. We have already mentioned the views held on the subject by two opposite schools of geologists; one maintaining that all Crystalline rocks have been derived from an internal permanently molten reservoir, while the other believes that some at least of the Crystalline rocks have been formed by extreme metamorphism of Derivative rocks.

It is unfortunate that those who have taken part in the controversy have looked, in many cases, only at a part of the facts on which the solution of the problem depends. A case is found in which Granite shows every sign of having been forcibly intruded in a fused state into the beds among which it occurs, and the observer thereupon jumps to the conclusion that all Granites are irruptive. Another observer detects Granite under circumstances which raise the strongest suspicion that it has been formed *in situ* by intense metamorphism, and forthwith refuses to believe that it has ever behaved irruptively. We have endeavoured to avoid these one-sided ways of reasoning by laying before the reader instances of both these methods of occurrence; and now the question arises, *Have these two forms been produced by different causes, or are they only the results of different stages of the same operation?*

There can scarcely be a doubt that bedded Granite, and the bosses of Granite that replace and pass gradually into the rocks that surround them, have been formed out of Derivative rocks by metamorphic action.

The process by which the change was effected must have consisted in a sort of softening and loosening of the particles of the rock to an extent that permitted a molecular rearrangement of its constitutents. In the case of the first form this was done without effacing the bedding; the second form resembles the first in every respect except that it shows no traces of bedding, and it is therefore reasonable to suppose that it is merely the result of a more advanced stage of the same process that gave rise to the first form. Now it is perfectly conceivable that the very same process, if carried still further, might work still more important changes. The softening might go on till the rock became actually fused, and in this condition, under the influence of increased heat and the pressure of the overlying beds, it might be driven forcibly through the rocks that surround it; thus the third or intrusive form of Granite would be produced.*

When we reflect how closely all these forms of Granite agree in average chemical and mineral composition and in lithological character, such a view as this seems *à priori* more probable than the theory which would compel us to draw an intrusive form of the rock from one source and the metamorphic shape of it from another. We cannot deny that two of the forms of Granite have been derived from sedimentary rocks by an advanced stage of the same process as gave rise to Gneiss, Mica Schist, and the rest of the rocks admitted to be metamorphic, and a still further development of the same operation seems to be perfectly competent to give us the third form; and it certainly looks more reasonable to accept this explanation, than to go out of our way to derive this third form from a source the very existence of which is, as we shall see by-and-by, somewhat problematical.

It must be added that there are certain peculiarities in Granite which seem to show that, like the rest of the Crystalline rocks, it could not be produced by the action of heat alone. When Granitic rocks have been fused artificially and allowed to cool slowly, the resulting product is altogether different from the original rock, though whether this is due to the rate of cooling not having been slow enough, or the pressure not having been great enough, or to what cause, we do not surely know. Again, its most infusible mineral, Quartz, instead of having been the first to crystallise, as would have been the case if the rock had been the result of fusion pure and simple, has in many cases been the last to solidify. We can realise how this may have come about, if Granite has been produced by what has been already described as hydrothermal action.†

If we admit in its entirety the doctrine that Granite and the other Trappean and Plutonic rocks had a metamorphic origin, we must go a step further and allow that lavas, which are only the subaërial shape of these rocks, were produced in the same way. We thus, by a long train of reasoning, have become convinced that what was pointed out as probable in the beginning of Chapter VI., has very strong evidence indeed in its favour, and that in all likelihood *all Crystalline rocks are the result of intense metamorphism of derivative deposits.*

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* For one case where intrusive Granite seems to have been produced by excessive metamorphism, see Quart. Journ. Geol. Soc. of London, xxviii. 105.

† Durocher has, however, attempted to show by a most ingenious line of reasoning how Quartz might retain a considerable degree of fluidity or plasticity down to a temperature far below its freezing point during the cooling of a molten mass having the same elementary composition as Granite (Comptes Rendus, 1845, xx. 1275). See also Vernon Harcourt, Report of Brit. Assoc., 1860, p. 181; Sorby on Mount Sorrel Sienite, Geol. and Polytech. Soc. of West Riding of Yorkshire, May 28th, 1863; Scheerer, Bull. de la Soc. Geol. de France, 2nd series, iv. 479, quoted by Scrope, Volcanoes, p. 283.

Objections to Metamorphic Theory.—Those geologists who dispute the metamorphic origin of Granite seem to rest their opposition mainly on two lines of argument. They say that the composition of the Crystalline rocks all the world over is so uniform, that it is not likely that they could have been derived from beds so variable as they assert the Derivative rocks to be; and they maintain that there is no Derivative rock which agrees in chemical composition with Granite.

The first of these statements is certainly not strictly true; and if it were, it would not prove the point it is intended to establish. Crystalline rocks are far from observing the constancy in mineral and chemical composition that is assigned to them. And if the assertion is only intended to be taken in a wide general sense, it will apply equally well to those Derivative rocks from which the metamorphic theory supposes Granite to be derived. Certain Sandstones looked at broadly are quite as uniform in composition as any Granite; and therefore there is no ground for surprise if, when these Sandstones are metamorphosed, the products also are very much alike. The first objection, therefore, falls to the ground.*

The second statement, that there are no Derivative rocks of the same composition as Granite, is decidedly open to question. Instances to the contrary might be multiplied without limit, but one example must suffice here. The two analyses given below are taken almost at random from Zirkel: (1) shows the composition of a Clay Slate from Prague; (2) that of a Granite in the Carpathians.

	(1)	(2)
Silica	67·50	69·31
Alumina	15·89	15·40
Lime	2·24	3·06
Magnesia	3·67	0·83
Potash	1·23	2·87
Soda	2·11	3·29
Oxide of Iron and Manganese .	5·85	1·79

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* See Allport, Geol. Mag., ix. 188.

There can be no difficulty, as far as chemical composition goes, in believing that the constituents of the first rock might be so rearranged as to give rise to something very like the second. But even if this objection were well founded, it would not be fatal to the metamorphic theory; for, since water plays so important a part in metamorphism, we can readily conceive that any ingredients necessary for the transformation of the rock into its new shape may have been introduced in solution either during or after the process of metamorphism.

Reasoning extended to other Plutonic Rocks.—We have so far confined ourselves to the particular instance of Granite, but all our arguments apply equally well to the whole body of the Trappean and Plutonic rocks.

In the first place there is no hard line separating Granite from the other Acidic members of those classes. In illustration of this it will be enough to repeat what we have already said about the close alliance between Granite and Felstone.

The lithological description and analysis of Granite show how closely it is related in composition to the more highly silicated Felstones. The main differences between them are these. In texture, the Granite being the more largely crystalline of the two; in the distribution of the Quartz, which in Felstone is usually so uniformly disseminated through the rock that it cannot be detected by the eye, while in Granite it occurs in lumps large enough to be easily recognised; in the presence of Mica, which occurs rarely in Felstone, but is universally found in Granite.

All these differences, however, are such as might well characterise two portions of the same molten mass which cooled under different circumstances; and they confirm the conclusions already arrived at, that the Granite produced by fusion consolidated under the pressure due to great depths below the surface, where the escape of heat would be very gradual, and where the consequent slow cooling allowed of the formation of a largely crystalline texture and a more complete separation of the constituent minerals.

We do find in Granite veins, and on the edges of Granite masses, where cooling must have gone on more rapidly than in the body of the rock, passages between Granite and Felstone: the Granite loses its Mica and passes into a rock known as Elvanite, and this again shades off into a rock indistinguishable from compact Felstone.*

Nor are our conclusions confined to Acidic Rocks. Details of one case where Basic as well as Acidic Trappean rocks seem to have proceeded from the metamorphism of Derivative rocks have been given on p. 293. The conclusions there arrived at have been confirmed by other observations in the same district. Thus Professor Geikie tells us of an intrusive sheet of a rock, which can be classed as Diorite, among the altered rocks of the Southern Uplands of Scotland, but which, in spite of its Trappean character, is found in the space of a few yards to pass into a rock which does not differ in general aspect from beds which are undoubtedly metamorphosed Felspathic Sandstones.* And he mentions that, while some of the stratified rocks, probably originally more quartzose, have been changed into Granite, others, which were probably more felspathic and argillaceous, have been altered into various Porphyries and Diorites.†

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* See the paper of Durocher's quoted on p. 322.

Summary and Conclusions.—We have now for the space of eight chapters been plodding through dry descriptions of various kinds of rocks, and explanations, some in the highest degree probable, others involving more or less of speculation, of the ways in which these rocks were originally formed and have been subsequently modified. A stone is no longer to us a stone and nothing more; every stone carries with it a story, and the experience we have gained enables us to decipher for each individual stone, with more or less of certainty, the characters in which that story is written, and translate it into our own tongue. But so far we have done little more than relate so many detached incidents in the history of the formation of the earth's crust, little more than collect a bundle of historical anecdotes, such as is put into the hands of children to awaken in their minds an interest for historical reading, and lead them up to the study of history itself. The question arises, is our geological knowledge as yet sufficient to enable us to do anything further than gather a budget of geological tales? Do the isolated facts we have been reviewing naturally lend themselves to a connected narrative? Can we ascend from them to broad general views, and frame out of them something deserving the name of a history of a portion at least of the lifetime of the earth on which we live? If it seems likely that we can, we shall do well boldly to make the attempt. For the history of every science shows that, if generalisations are made in a truly cautious and philosophical spirit, and when necessary, looked upon as merely provisional working hypotheses, the gain that follows from them is immense; nay more, that if they are not made when the right time for making them has arrived, the loss that results is still greater. Not only do well-grounded hypotheses serve as a string on which to hang our facts, where they can swing in full view and be readily got at when wanted, but they also point out the direction we must go in if we wish to add to our collection. And in the opinion of many eminent thinkers the time is ripe for some degree of generalisation in Geology. It matters not that many pages of the geological record are so blurred and blotted that we can only grope our way stumblingly through them; that many can be read in several different ways, so that the interpretations of them are almost as numerous as the interpreters; that many are altogether blank, and many torn out and gone for ever. We take heart, when we find very many written in characters which cannot be misunderstood, and find too that the pages we can read are numerous enough to justify us in attempting conjectural restorations or emendations of those which are lost or corrupt.

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* Memoirs of the Geol. Survey of Scotland, Explanation of sheet 3, par. 26.

† Ditto, Explanation of sheet 15, par. 35.

The hypothesis by which we propose to endeavour to connect together the isolated facts that have been laid before the reader has been pretty clearly hinted at several times over in the last three chapters. We will now put it in a formal shape, with the caution that, though it has for some time been finding its way more and more into favour, it must still be looked upon as no more than a probable speculation.

We have found that Granite occurs under three forms. Under the first form it still retains traces of bedding or is interstratified with undoubtedly bedded rocks; here there can be little doubt that it is an intensely metamorphosed rock. Under the second form Granite occurs in amorphous masses, which melt away insensibly on all sides into unaltered strata, show no signs of having burst violently through the adjoining beds, but look as if they filled up spaces once occupied by rocks similar to those that surround them. Such appearances are best explained by supposing that portions of the rock-mass, in the heart of which these bosses occur, have been altered into Granite, the metamorphism having been more intense than that which produced the first form of the rock because the bedding is effaced, but yet not energetic enough to cause the Granite to behave irruptively. Under its third form Granite gives proof of having been forcibly intruded into the rocks among which it occurs, and its irruptive behaviour may reasonably be attributed to an increased degree of energy in the metamorphic process which gave rise to it. 3

There is reason, then, to believe that these three forms of Granite have not been produced by different causes, but are the results of three successive stages of the same process; and now that we seem to have seen our way to three links in a chain of operations, we are led on to inquire whether any others of the geological processes we have become acquainted with may not belong to the same series, and to try and assign to them their proper places in it.

Now the metamorphism which produced bedded Granite differs in all probability from that which gave rise to Gneiss and less highly altered products, only in intensity. On the one side, then, we have a passage from the bedded form of Granite through Gneiss and other Metamorphic rocks into the Derivative rocks, out of which the latter were produced. Here, then, we seem to have an unbroken chain linking on Derivative rocks to one form of Granite.

Looking in the other direction, the bedded Granites pass through the second form of that rock into Granites which have been shifted from the spot where they were metamorphosed and driven violently into rents and fissures. If such openings fail to reach the surface, the injected masses harden under pressure, and give rise to Trappean and Plutonic products. The passage, for instance, that has frequently been observed between intrusive Granite through Elvanite into compact Felstone (Petrosilex), shows one case of a Trappean rock which is nothing but Granite modified by the circumstances under which it cooled. But if Granite should be injected into a vent opening above ground, we can scarcely doubt that the portion of it which hardened under ordinary atmospheric pressure would take the form of Trachyte.

On this side, then, Granite is connected with one of the commonest forms both of the deep-seated and subaërial crystalline rocks.

The complete chain of operations, then, would seem to be as follows. First, Derivative rocks are formed by the wear and tear of crystalline strata. Certain of these Derivative rocks, coming within the range of metamorphic action, pass through various stages of metamorphism into Gneiss, and thence into the three successive forms of Granite. By the final step an intrusive product is obtained, which, if it harden under pressure, takes the form of a Plutonic or Trappean rock of Acidic composition, such as Granite, Elvanite, or compact Felstone; but if it be ejected on to the surface, hardens into an acidic lava, such as Trachyte. And so, in the end, we come back to the Crystalline rocks with which we started.*

Granite has been selected as a particular instance for illustrating this great cycle of changes, but the line of reasoning applies equally well to all the members of the Plutonic and Trappean classes of rocks.

Derivative rocks of suitable composition are capable, when subjected to the same process, of giving rise to Basic and other varieties both of deep-seated and subaërial Crystalline rocks.

If the hypothesis just explained be true, we might expect to find that periods of great metamorphism would be also periods of great volcanic activity. Professor Geikie has pointed out one instance in which this has certainly been the case;† and he has suggested a very probable reason for this connection, which we shall have to consider when we come to inquire into the cause of volcanic energy.

An attempt has been made to present to the eye a diagrammatic representation of the round of changes from Derivative to the different forms of Metamorphic and Igneous rocks in Fig. 54.

On the right, widespread regional metamorphism is going on over a large area, the action increasing in intensity from left to right. On approaching this tract the bedded rocks gradually put on metamorphic forms, and shade off into Gneiss and bedded Granite; as we get more into the heart of the metamorphic region, the latter passes into molten amorphous Granite. The beginning of the change, and the final passage into Granite, take place at a greater distance from the metamorphic centre in some beds than in

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* See the paper of Mr. Judd's, already referred to, on the Secondary Rocks of Scotland. Quart. Journ. Geol. Soc., xxx. 233—237, 289—295; A. Geikie, The Geology of East Berwickshire (Memoirs of the Geol. Survey of Scotland), p. 33; Ramsay, Address to Geol. Section of British Association, 1866.

† Transactions Edinburgh Geol. Soc., ii. 287.

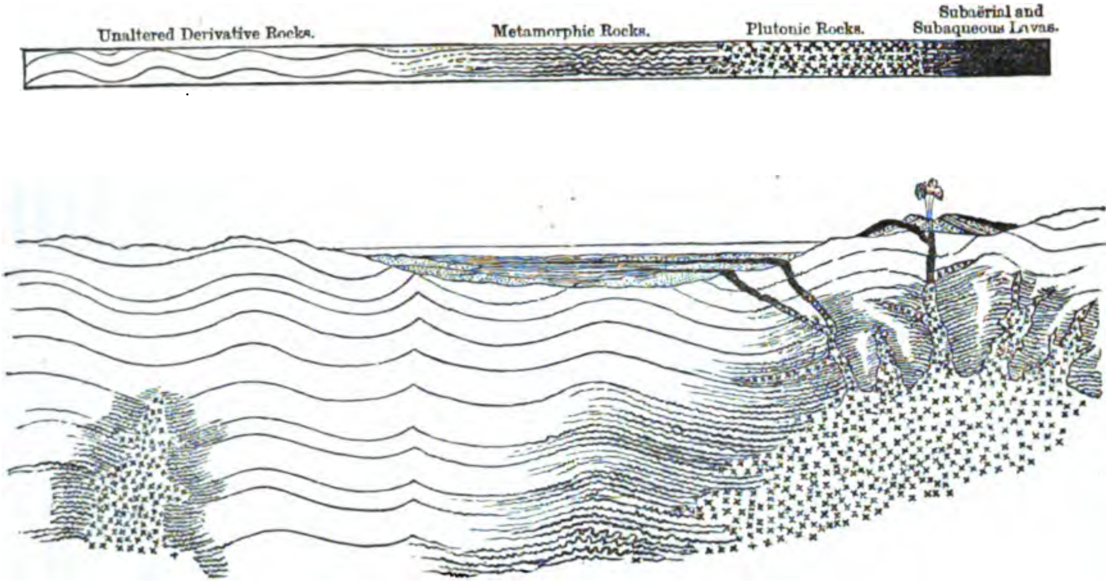

Fig. 54.—DIAGRAM TO ILLUSTRATE THE RELATIONS OF DERIVATIVE, METAMORPHIC, PLUTONIC, AND VOLCANIC ROCKS.

others, those first affected being more susceptible of metamorphic influence than the strata above and below them. In this way we get along the margin of the metamorphic region *beds of Granite* interstratified with crystalline Schists. Still further to the right, where the metamorphic energy has reached its maximum, portions of the fused Granite have been injected into the overlying rocks. Some of the vents do not reach the surface, and the matter that hardens in them gives rise to intrusive Plutonic or Trappean processes; two other vents do reach the surface, and the portions of the fused mass that are forced up through them flow out and harden into lavas, some of which are poured out on land, and others, streaming over the sea-bed, become interstratified with the derivative deposits that are being laid down beneath the water.

To the left is a centre of local metamorphism, around which portions of the Derivative rocks are converted into Granite; here, owing to the smaller intensity of the metamorphism, none of the molten matter has behaved intrusively; the irregularities in outline of the Granite masses are not caused by intrusion of that rock, but are due to the fact that some beds are more readily metamorphosed and converted into Granite than others, and accordingly the process of change has spread further into them than into the strata less open to alteration. A belt of altered rock fringes this mass, and also the Granite dykes to the right; but it will be noted that this is much narrower than the broad band of altered rock which abuts against the tract of regional metamorphism.

Classification of the Crystalline Rocks based on the Metamorphic Theory.—In the case of the Non-Crystalline rocks, all our attempts to classify them in a satisfactory manner failed so long as we neglected to take into account the way in which they were formed. But as soon as we were able to show that they had all arisen directly or indirectly from denudation, we saw our way at once to a comprehensive and natural scheme of grouping, which under various hands might assume various forms as far as details go, but in general outline would resemble the arrangement attempted on page 180.

In the same way, when we came to deal with the Crystalline rocks, we found the ordinary classification of them defective and often inconsistent, because it failed to pay attention to the method of their origin. But if we can show that the Crystalline rocks all owe their existence ultimately to a common cause, or if we could subdivide them into a number of groups in each of which all the members had a common origin, we should then begin to have hopes that they too might be brought under a natural and consistent arrangement.

It is hardly yet time to assert, that the theory which refers all Crystalline rocks to various stages of metamorphism, is securely established; but the probability of this view ultimately turning out to be correct is so great, that it is worth while trying what sort of a classification it would lead to, if it were true.

Now there are three things we want to learn about a rock, if our knowledge of it is to be complete:—

1st. The way in which it was produced.
2nd. The petrological manner of its occurrence.
3rd. Its mineral composition.

In the case of the Crystalline rocks the answer to the first question resolves itself, according to our present views, into a statement of the degree of metamorphism each rock has undergone, and under this head we can distinguish three stages.

1st Stage, in which some traces of the originally bedded character of the rock still remain. The rocks of this stage may be called METAMORPHIC, and divided into *Non-Foliated* and *Foliated*.

2nd Stage, when the bedding has been entirely effaced and a crystalline amorphous mass produced, *but the product does not behave intrusively*. These rocks may be called NON-INTRUSIVE-PLUTONIC.

3rd Stage, a further advance on the last, by which the crystalline products have been enabled *to burst through the surrounding rocks*. Under this head there are two subdivisions. The first includes those portions of the intrusive mass which never reach the surface, and harden under pressure. These may be distinguished as INTRUSIVE-PLUTONIC, or IRRUPTIVE. The second subdivision takes in the rocks which burst out on to the surface and form subaërial or submarine flows. These may be styled ERUPTIVE.

Our next care will be to specify the petrological form under which each rock presents itself; and the principal petrological forms under which Crystalline rocks occur, are —Beds, *i.e.* true strata, Masses, Dykes, Veins, Necks, Intrusive Sheets, and Contemporaneous Sheets or Flows.

Lastly, the mineralogical composition may be denoted by an adjective, such as Granitic, Dioritic, Basaltic, and so on.

The general scheme, then, will stand as under :—

GENERAL CLASSIFICATION OF CRYSTALLINE ROCKS.

Method of Formation.	Mode of Occurrence.	Principal Mineralogical Varieties.	
A.—METAMORPHIC	More or less distinctly bedded	Non-Foliated.	Quartzite, Porcellanite, Crystalline Limestone, some Granitic rocks.
		Foliated.	Schists, Gneiss, Granitic Gneiss.
B.—NON-INTRUSIVE PLUTONIC	Masses		Felsitic, Dioritic, Granitic, Syenitic, &c.
C.—IRRUPTIVE	Masses Dykes Veins Sheets		Felsitic, Trachytic, Basaltic, Doleritic, &c.; some Granitic, Syenitic, and Dioritic rocks.
D.—ERUPTIVE	Flows Necks Dykes		Felsitic, Trachytic, Basaltic, Doleritic, &c.

The terminology of the first column of the above table is by no means all that could be wished for. The restriction of the term Metamorphic to one class of a body of rocks, the whole of which are, according to our statement, of metamorphic origin, is undesirable, and Non-Intrusive Plutonic is the reverse of elegant. But it will be time enough to set about coining new terms when it is seen whether the scheme now put forward tentatively meets with approval. Till then, it seemed better to adopt terms already in use, even though they are employed in a sense slightly different from their common acceptation.

An application to one or two actual instances will perhaps make the above scheme more intelligible. The stratified Granites of Donegal will according to it be described as *Granitic Metamorphic Beds*. The Granite of

Priestlaw will be a *Granitic Non-Intrusive-Plutonic Mass.* The Granites of Devon and Cornwall will be *Granitic Irruptive Masses.* In Arthur's Seat the Intrusive Sheets of Trap will be *Doleritic Irruptive Sheets;* the interbedded Traps, *Doleritic Eruptive Flows*, or simply *Doleritic Flows;* the rock of the summit a *Basaltic Eruptive Neck*, or simply a *Basaltic Neck.* Necks and Flows being necessarily Eruptive, the adjective in their case may be dropped.

CHAPTER IX.

HOW THE ROCKS CAME INTO THE POSITIONS IN WHICH WE NOW FIND THEM.

"They are raised for ever and ever
And sink again into sleep."
TENNYSON.

SECTION I.—NATURE OF THE DISPLACEMENTS WHICH ROCKS HAVE UNDERGONE.

WE have now learned the ways in which the different kinds of rocks composing the earth's crust were formed, and the modifications of structure which some of them have undergone since their formation; our next step will be to inquire into the changes of position they have suffered, and how these changes were brought about.

Displacements which Submarine Beds have Suffered.—A large number of the rocks of the earth's crust were originally formed in approximately horizontal beds at the bottom of the sea, but this is not the position we now find many of them in. They have frequently undergone two very important displacements.

First, they have been raised high and dry into the air, sometimes even up to the summits of lofty mountains; secondly, the beds into which they are divided are no longer horizontal, but inclined to the horizon at all angles from the gentlest slope up to becoming absolutely vertical, oftentimes bent into broad folds or puckered up into the sharpest and most complicated curves, in some cases even turned over, so that the stratum originally at the bottom is now uppermost.

It will conduce to clearness of ideas if for the present we consider these two displacements, the upward rise of the beds and the displacement of them from their originally horizontal position, as separate facts; but we shall see in the end that it is very possible they are both due to the same cause.

SECTION II.—VERTICAL ELEVATION.

Two possible Explanations of Elevation.—The presence of beds, which were formed beneath the sea at different heights above its present level, may be accounted for in two ways. Either the sea has shrunk and had its level lowered, or tracts which were once beneath its waters have been raised into dry land, other tracts being depressed to form receptacles for the water thus displaced.

Arguments against a Lowering of the Sea-level.—There are many insuperable difficulties in the way of accepting the first explanation. According to it, the ocean must have stood in some cases upwards of ten thousand feet above its present level, and, as a rise in the sea-level must be universal, the whole of the globe must have been submerged to this depth. Here we are at once met by the difficulty of getting rid of so enormous a bulk of water, a difficulty which is very much increased by the fact that Geology shows that the relative level of the sea and land has oscillated upwards and downwards over and over again; so that we have not a general decrease in the waters of the ocean to account for, but countless repetitions of alternate swelling and shrinking.

Further, to take a particular instance, marine strata, belonging to what is known as the Nummulitic formation, are found in the Alps and other mountains at a greater height than that just named; if the sea ever reached up to the level where they now occur, nearly the whole earth must have been under water, and nothing would have been left in the shape of dry land but a few islands formed by the peaks of the highest mountains. But in France and England there are Estuarine and Lacustrine deposits containing the remains of land animals, of the same age as the Nummulitic beds, and this shows that at the time when the latter were being formed extensive tracts of land existed at no great distance from the spot where they attain so great an elevation. It is evidently impossible that the sea-level should have retained its present position in England and France, and at the same time stood so much higher in Switzerland. Besides, the very existence of Derivative rocks requires land, from the waste of which the materials necessary for their formation may be derived. But where shall we find land enough if the whole globe was submerged to these great depths?

Again, the hypothesis of the lowering of the sea explains only one-half of the facts we have to account for; no alteration in the depth of the ocean will tilt beds originally horizontal, or fold and contort them.

The Land has gone up, not the Sea gone down.—For these and other similar reasons we cannot allow of the possibility of such oscillations in the sea-level as are required by the first explanation, and are driven to attribute the occurrence of marine beds in inland and lofty situations to an elevation of the sea-bed, by which tracts once below its waters have been upraised and turned into dry land.*

Denudation gives Proof of Elevation.—The phenomena of denudation point to the same conclusion. The wear and tear of the land, which is everywhere going on slowly but without ceasing, if it had been allowed free play without any counteracting influence, must long ago have swept away everything exposed to its action, and have reduced the land to a dead flat but little raised above the sea-level.

This has not happened, and there must have been therefore some antagonistic force at work to counteract the levelling tendency of denudation. Just what we want would be supplied by forces of elevation, which from time to time raised sea bottoms into dry land, and so formed new continents to take place of those which had been worn down by denudation.

Instances of observed Oscillation of Land.—Considerations such as these would be quite enough to convince us that changes in the relative level of the land and sea have occurred, and have been produced by movements of the solid crust, and not by an alteration in the bulk of the ocean, even if no cases of such movement had actually come under observation. Our position will, however, be all the stronger if we can point to actual instances where movements of the land have been observed, and this we fortunately can do.

The well-known case of the Temple of Serapis, at Puzzuoli, near Naples, shows that within the historic period the spot where it stands was once beneath the sea; was afterwards upraised and became the site of a temple older than the one whose remains are now standing; was possibly again submerged and again upraised before the building of the present ruin; was again let down till the sea rose at least some twenty feet above the pavement of the temple; was again raised into dry land, and is now slowly sinking again.*

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* The whole question is lucidly treated by Playfair, Works, i. 432.

Then again we have the case of the Scandinavian peninsula, where there is good reason to believe that within the memory of man the northern part of the country has been rising, perhaps at the rate of two or three feet in a century; that the movement lessens as we go southwards till about Stockholm the land is stationary; and that still further south motion is going on in the opposite direction and the land is slowly sinking.† It will be seen how a case like this, and it is not an isolated one, effectually disposes of any attempt to explain the phenomena we are considering by a lowering of the sea-level.

We have distinct proofs of oscillations of level in our own country at no very distant period. Every here and there round the northern part of the island we find, at a height of from twenty to thirty feet above the present mean-tide level, a flat terrace stretching inland for a distance varying from a few yards to several miles, and bounded on the landward side by a line of bluffs, bearing a strong resemblance to a sea-cliff. The subsoil of this terrace consists of Sand, Silt, and Shingle, occasionally enclosing shells and other marine remains, and in some cases human implements and canoes. This terrace is evidently an old sea-beach, and shows that the land at one time stood some twenty or thirty feet lower than it does now, and remained in that position long enough to give the sea time to cut a notch in the solid rock as a record of its former level, and to strew the floor of that notch with shore deposits. In the elevation that followed the land was raised to a greater height than at present, for we constantly find stretching out below the sea the remains of buried forests, the trees of which not only grew on dry land, but could have attained their size and luxuriance only in situations sufficiently far inland to be removed from the blighting influence of sea breezes. We have, therefore, evidence of a time when the land was lower than now, of a subsequent upheaval which raised it above its present level, and in fact probably connected it with the continent of Europe, and afterwards of a depression which produced its present insular condition.*

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* For details, see Lyell's Principles, vol. ii. chap. xxx.; Quar'. Journ. Geol. Soc., iii. 186.

† Lyell's Principles, vol. ii. chap. xxxi.

Submergence produced by a Polar Icecap.—There is one possible means by which a change might have been produced in the position of the sea-level without any movement on the part of the land, that ought not to be passed over.

We have evidence that there have been times when the climate of the polar and temperate regions became far more severe than at present, and it seems likely that these cold periods shifted from one hemisphere to the other perhaps several times over during a long lapse of years. It has been supposed, that, in consequence of this, enormous accumulations of ice gathered, now round the northern and now round the southern polar regions, which reached down far into the temperate zones. Should such caps of ice ever form around the poles, their attraction would tend to draw the water of the ocean towards the pole around which they were placed, and so raise the ocean level in the corresponding hemisphere.

There is, however, considerable doubt whether this cause has ever really been in action. That there have been these periods of intense cold is beyond question; but there is no evidence to show that there ever was a continuous cap of ice spreading away in every direction from the pole. There is distinct proof that during these times every region, whose configuration made it a good gathering ground, became a great snow-field, and a centre from which ice-sheets and glaciers were shed off, but all the known facts are dead against the idea of the northern regions having being ever swathed in one general covering of ice.†

SECTION III.—DISPLACEMENT OF THE ROCKS FROM THEIR ORIGINALLY HORIZONTAL POSITION.

The instances we have given furnish proof of up and down movements, by which rocks formed beneath the sea are raised above its level. But this is not all that has happened to them. In the case of stratified deposits we know that their beds must have been at the time of their formation approximately in a horizontal position; there would be exceptions when sediment was thrown down by currents in sloping layers, but these are unimportant in a general view, and, speaking broadly, we may say that beds of sedimentary rocks were originally horizontal. But this is not the positon in which, in many cases, we now find them, and hence we learn that rocks have been affected by other movements besides that of mere vertical elevation. A moment's reflection on the way in which sedimentary rocks were formed would be quite enough to convince us that they could not have been deposited in the inclined positions in which we often see them; but one or two other facts leading to the same conclusion may be just mentioned. The surface of such beds often bear ripple-marks, rain-pittings, and the tracks of animals, which could not possibly have been impressed on them in their present highly inclined position. We occasionally find embedded in rock the trunks of trees still rooted in the soil in which they grew, and inclined at the same angle to the vertical as the beds are to the horizon. We cannot suppose these trees grew in such an unusual position; but if we suppose them to have sprung up when the beds were horizontal, and to have shared in a subsequent tilting, their position will be satisfactorily explained. Again, if we examine a deposit of Shingle we find a tendency among the pebbles to arrange themselves with their flat surfaces and longer axes horizontal; but wherever we find inclined beds of old Shingle or Conglomerate, the flat surfaces of the pebbles are parallel to the bedding, showing that, since the former were deposited horizontally, the same must have been the case with the latter.

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* For other cases of oscillation of level, see Geol. Mag., vol. viii. pp. 300, 430; Nature, i. 381.

† On this subject, see Adhemar, Révolutions de la Mer (Leipzig, 1843); Croll, The Reader, Sept. 2nd, Dec. 2nd, Dec. 9th, 1865, Jan. 13th, 1866; Phil. Mag., 4th series, xxxi. 301 (Ap. 1866); Heath, Phil. Mag., 4th series, xxxi. 201, 323; Pratt, Phil. Mag., 4th series, xxxi. 172, 532; Figure of the Earth, 4th ed., p. 236; O. Fisher, The Reader, Feb. 10th, 1866; and The Reader, 20th Jan., Feb. 24th, March 17th, 1866; and for a summary, Croll's "Climate and Time," chap. xxiii.

We will now go on to consider the displacements rocks have undergone from their originally horizontal lie, and define the terms used in describing them.

Dip.—Where strata have been tilted from a horizontal position, their inclination to the horizon is called the *Dip*. The amount of dip may be stated in degrees, or by saying that the bed rises or falls so much in a given distance. Thus, in Fig. 55, if ABC be the surface of an inclined stratum, OBC a horizontal plane, AO vertical and AD perpendicular to BC, the angle ADO is the dip of the bed; and if this angle be measured and found to be 19 degrees, we may say that this is the amount of the dip; or since *D O* is in this case three times as long as *A O*, we may say the dip is 1 in 3, or 12 inches to the yard. The bearing of the line *D O*, which may be determined by a compass, is the direction of the dip.

Strike.—The line *B C*, or the intersection of the inclined bed with a horizontal plane, is called its *Strike or Level line*, and is described by its compass bearing.

Perhaps the simplest illustration of dip and strike may be given by holding a board or slate in an inclined position in a trough of water. The intersection of the surface of the water with the slate is necessarily horizontal, and gives the line of strike; if a drop of water be placed on the slate it will run down the steepest line on it, and this is the line of dip. In practice a quarry partly filled with water is the best possible place for determining dip and strike.

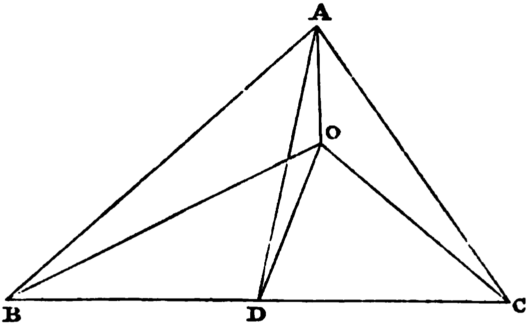

Fig. 55.

To put the definitions as shortly as possible, we may say that the line of dip is the line of *greatest inclination* that can be drawn on the surface of a bed; the line of strike is the line of *no inclination*.

Measurement of Dip.—If we have the surface of a bed laid bare, we can determine, by an instrument for measuring angles, called a Clinometer, the direction of a level line on the bed, and then, by measuring the inclination along a line at right angles to the level line, we get the amount of the dip. Or the dip may be measured on an exposed face of rock, such as a cliff or the wall of quarry; but in such a case, in order to determine its full amount, it is necessary that the face should be, like *A O D*, perpendicular to the strike; if, for instance, a measurement was made on faces such as ABO, ACO, the observed angles would be less than the full amount of the dip.[*]

In practice it often happens that we cannot find a vertical face running along the true dip; but we can generally get measurements of the apparent dip along two faces, making a large angle with one another, from which the amount and direction of the full dip may be determined by calculation,[†] or by a graphical method given in the *Geological Magazine*, X. 332. A little practice, however, will generally enable us from two such observations to make an estimate of the full dip quite near enough for all practical purposes.

Outcrop.—The line along which a bed cuts the surface of the ground is called its *Outcrop* or *Basset*. If the surface be horizontal, the outcrop and strike will coincide, but this will not be the case on undulating ground unless the bed be absolutely vertical; for all other inclinations the outcrop will wind about with the inequalities of the surface, and the bendings will be larger the smaller the dip.

The way in which the outcrop of a bed of moderate inclination winds round hills and runs up and down valleys is at first somewhat puzzling, and any attempt to explain it verbally would only lead to increased confusion. The beginner will derive much assistance from models such as those of Mr. Sopwith, or he may construct rude models for himself by laying a few layers of putty, separated by sheets of coloured paper, in an inclined position, cutting valleys across them, and noting the difference in the figures formed by the edges of the paper, according as the ground is inclined in the same direction as the beds or not, and as the slope of the surface is greater or less than the dip of the beds; he will be in a better case still if he has an opportunity of examining an

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[*] For tables giving the amount of dip along a line inclined to that of the full dip, see Jukes's Manual, Appendix I., and the Geology of the South Staffordshire Coalfield (Memoirs of the Geol. Survey of England), p. 215.

[†] Let d and d' be the two observed dips ABO, ACO, D the full dip ADO: $BOC = 2a$, $BOD = a - b$, $COD = a + b$, then

$$\text{Tan } b = \frac{\sin(d - d')}{\sin(d + d')} \cot a$$

$$\text{Tan D} = \frac{\sin(d + d')}{2 \cos a \cos d \cos d' \cos b}$$

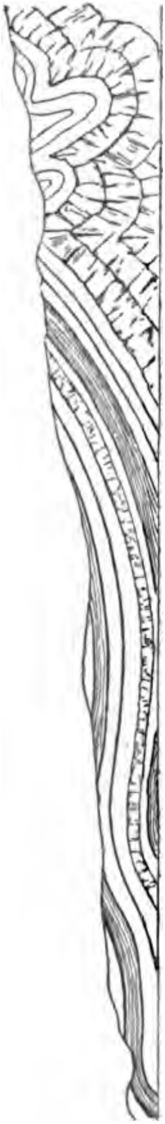

Fig. 56.—Undulating and Contorted Beds with a general Dip in one Direction.

undulating country where the run of the beds can be easily traced.

Undulations and Contortions.—It very rarely happens in nature that the dip of the bed is constant for any long distance; it frequently varies both in amount and direction from point to point. When the changes are small and gentle, a series of easy rolls or undulations is produced. In other cases the foldings are excessively sharp and sudden, and the beds are then said to be *contorted*.

Undulations and contortions may be present on a small scale without interfering with the general dip of the beds; thus, in Fig. 56, the beds on the left have been thrown into a series of broad gentle folds, and towards the right have been puckered up into sharp curves, but preserve, in spite of these lesser irregularities, a general dip from the right towards the left.

A case of violent contortion on a small scale is given in Fig. 57, which is a natural section of Shale and thin Sandstones in North Staffordshire.

Fig. 58* shows another case, where beds of solid Limestone have been bent to the form of an inverted W. It is in mountain chains that such foldings and crumplings occur on the grandest scale, the beds sweeping up and down in curves of enormous radius, and bending in and out in countless and most abrupt plications. This structure has been found to a greater or less degree in all mountain chains that have been geologically examined; a fact to be carefully borne in mind, because the invariable presence of intense contortion in all elevated ranges throws, as we shall see in

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* Roughly reduced from a photograph issued by the Geological and Polytechnic Society of the West Riding of Yorkshire.

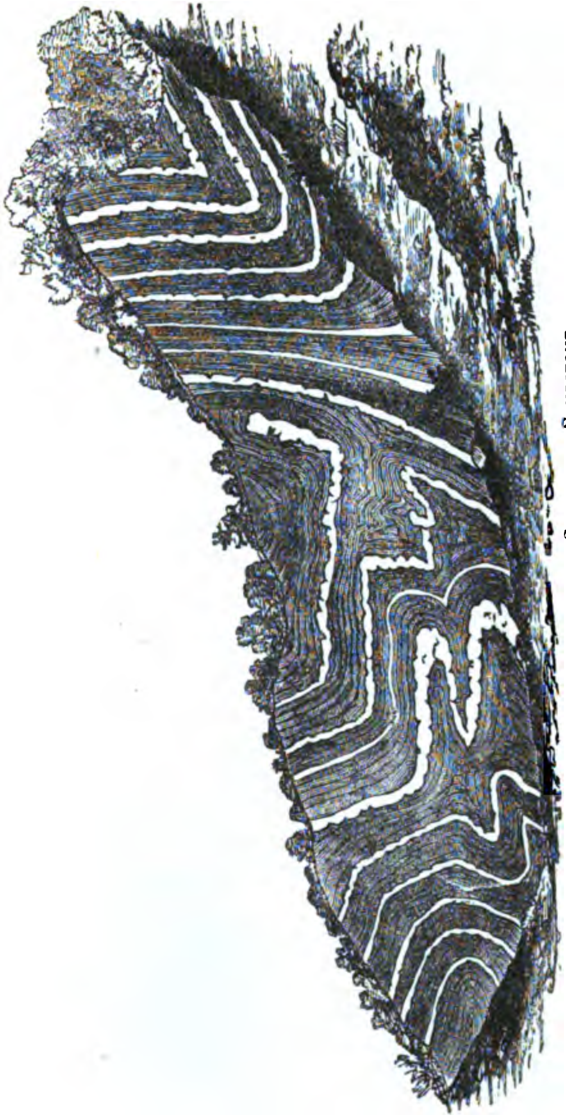

Fig. 57.—Contortions in Shale and Sandstone.

Chapter XI., great light on the theory of the process of mountain formation.

The following terms are used in connection with the larger undulations.

Anticlinal and Synclinal; Dome and Basin.—When the beds have been bent into the form of arches, these are called *Anticlinals* or *Saddles*, and the hollows between them *Synclinals* or *Troughs*.

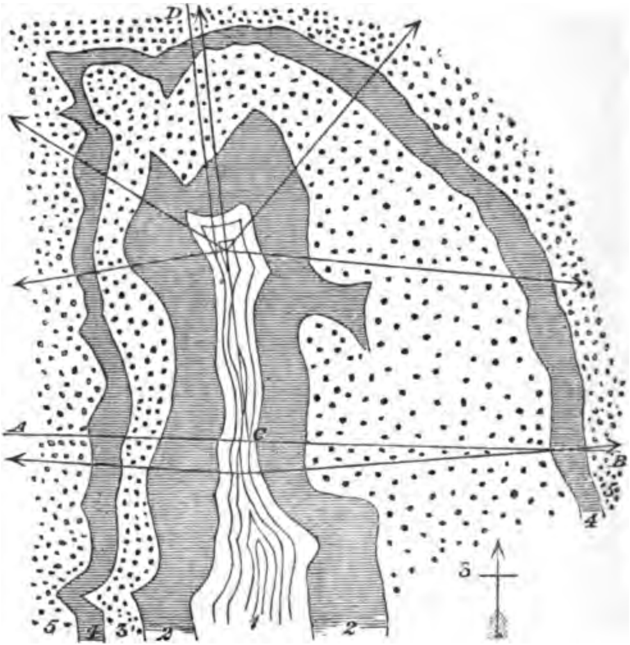

Fig. 59.—MAP OF AN ANTICLINAL.

In both Anticlinals and Synclinals the line in each bed, along which the change in the direction of the dip takes place, is called the *Anticlinal or Synclinal Axis* of that bed; and the planes containing all the axes of an anticlinal ridge or synclinal trough are called *Axis planes*.

If the beds dip away in all directions from a centre, they are said to have a *quaquaversal dip*, or to be *domed;* and if they dip everywhere towards a centre, they have a *centroclinal dip*, or form a *basin*.

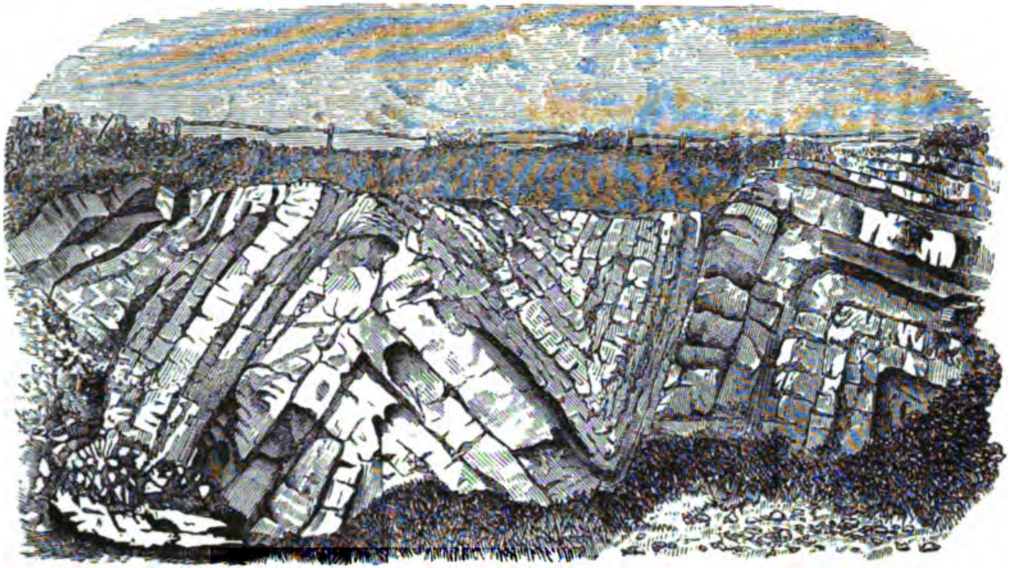

Fig. 58.—Contorted Limestone, Draughton, near Skipton.

An anticlinal runs on as long as its axes are horizontal or only gently inclined; it is brought to an end when they begin to bend down sharply. A complete anticlinal consists of a long ridge terminated at each end by the half of a dome; in fact, an anticlinal is nothing but an elongated dome. A synclinal, in the same way, is a long trough with half a basin at each end, or an elongated basin.

Anticlinals and synclinals are, however, often abruptly truncated by the dislocations known as faults.

Anticlinal.—A sketch map and sections of an anticlinal ridge are given in Figs. 59, 60, and 61, the arrows showing the direction of the dip. In the southern part of the map the beds are thrown off both to the east and west from a central line or axis, as shown in the section, Fig. 60; their outcrops wind about with the inequalities of the ground, but keep on the whole a northerly and southerly strike. On the east, owing to the smaller dip and the flatness of the surface, the outcrop of No. 3 is much broader than on the west side. Towards the north, however, the regular dip to either side becomes gradually exchanged for a dome-shaped bedding, the strata fall away in all directions, and the anticlinal is terminated by a half dome, around which the easterly and westerly outcrops bend till they join one another. The second section shows this change in dip; its southern part runs along the anticlinal axis, and the beds are therefore

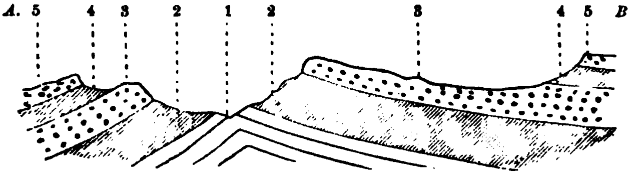

Fig. 60.—Section along the Line *A B*, in Fig. 59.

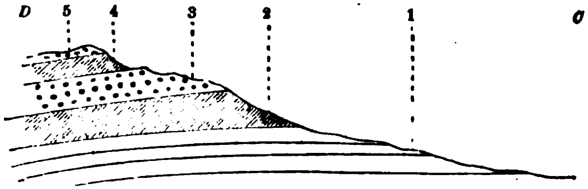

Fig. 61.—Section along the Line *C D* in Fig. 59.

flat, but towards the north they bend down, and the successive members come on one over the other, just as along the flanks of the arched area on the south.

Dome.—As an illustration of dome-shaped bedding, or quaquaversal dip, I have chosen Simon's Seat, a conspicuous hill in Wharfedale, the structure of which has been kindly explained to me by my friend Mr. J. R. Dakyns.

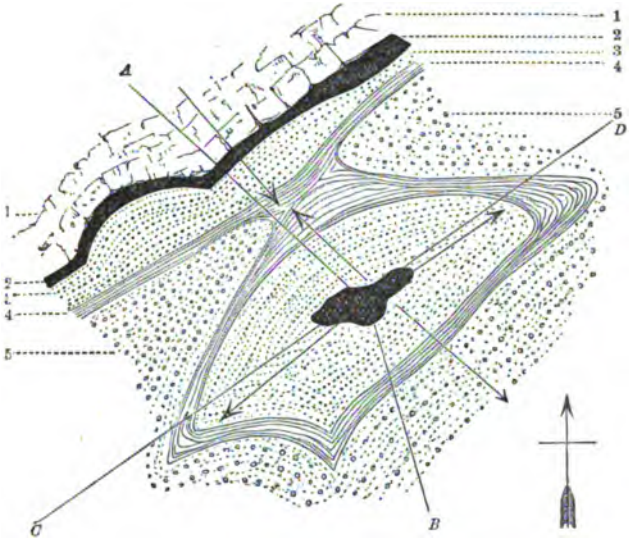

Fig. 62.—Geological Sketch-map of Simon's Seat.
Scale 1 inch to a mile.

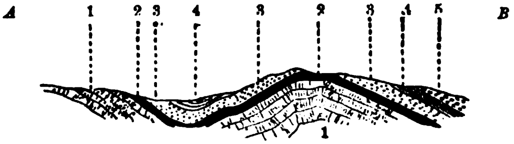

Fig. 63.—Section along the Line *A B* in Fig. 62.

Figs. 62, 63, and 64 show a sketch plan of the hill and two sections across it. The rocks of which it is composed are—

5. Gritstone. (Top.)
4. Shale.

3. Gritstone.
2. Shale.
1. Limestone. (Bottom.)

The beds, as shown by the arrows on the plan and by the sections, dip away in all directions from a centre, around which their outcrops run in concentric curves. Thus in the middle we have a patch of No. 2; this is enclosed by a belt of No. 3, which is in its turn surrounded by a ring of No. 4. The outermost band, formed by the outcrop of No. 5, is not complete, a portion having been removed by denudation. The Limestone does not actually come to the surface in the centre of the dome, but it is brought up by a change of dip on the north-west side of the hill, and seen to underlie the Shale No. 2, and it must therefore form the great mass of the interior of the hill.

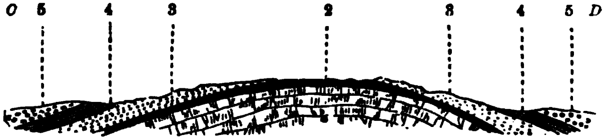

Fig. 64.—Section along the Line *C D* in Fig. 62.

Very beautiful illustrations of domes are sometimes seen on the sea-coast, when the waves have planed away the summit and laid bare a horizontal section perpendicular to the axis of the dome. A good instance occurs near Berwick-on-Tweed. The rocks consist of alternations of hard Limestones or Sandstones and soft Shales, and at one spot they have been thrown into a dome almost perfectly circular in outline. The top of this has been sliced across in the way just mentioned, and the concentric rings formed by the outcrops of successive beds are most distinctly exhibited. The structure comes out with singular clearness, because the outcrop of each hard bed stands up above those of the softer measures on each side; and thus there is produced a set of concentric circular low reefs, separated by grooves in which water remains after the fall of the tide has laid all around dry.

Synclinal and Basin.—A case of a synclinal trough is shown in Figs. 65, 66, and 67, which are a map and sections of a part of a long synclinal in North Staffordshire, known as the Goyt Trough.

The general synclinal lie over the greater part of the

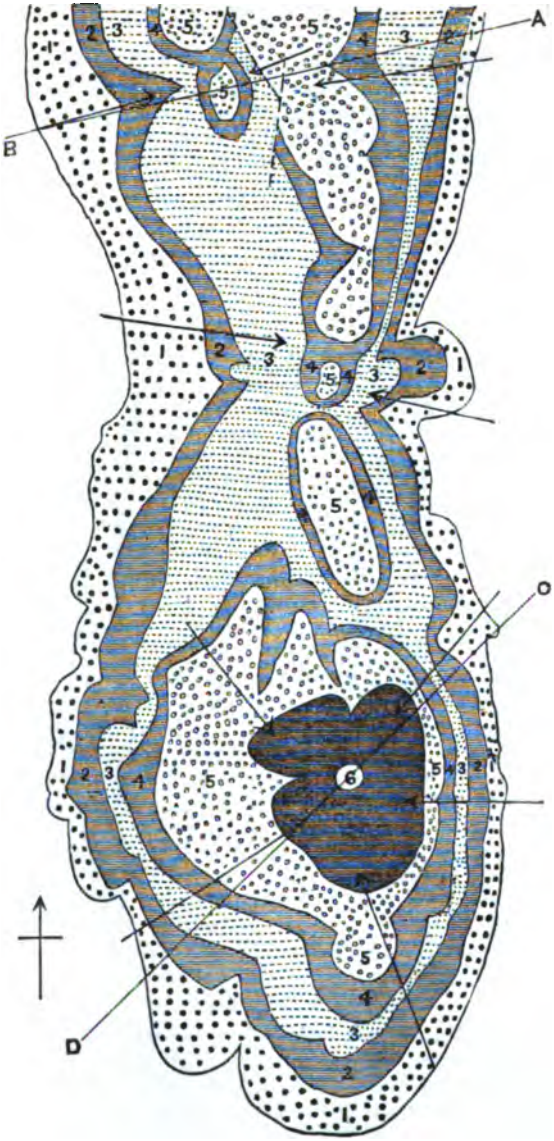

Fig. 65.—Geological Sketch-map of a Part of the Goyt Trough.
Scale 1 inch to a mile.

map is well shown by the beds 1, 2 and 3, whose outcrops, in spite of windings due to inequalities in the ground, strike persistently north and south, and which dip inwards on both sides towards a central axis, as shown in the second of the sections. The trough, however, is subdivided by lesser undulations into several minor basins. The first section runs across one of these. Here the general easterly dip of the western half of the trough is exchanged about the centre for a dip to the west, and a smaller interior trough produced. The beds then roll over and resume their easterly dip up to a fault, beyond

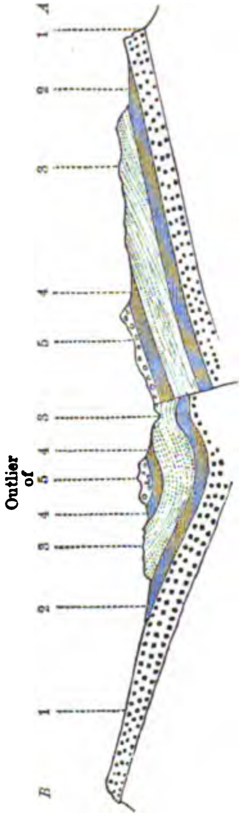

Fig. 66.—Section along the Line *A B* in Fig. 65.

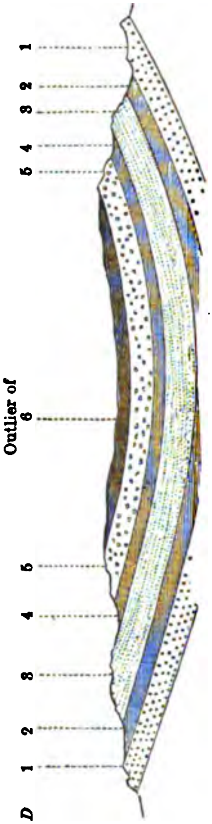

Fig. 67.—Section along the Line *C D* in Fig. 65.

which they put on the westerly dip which prevails along the eastern half of the trough.

Another well-marked basin, in the centre of which a detached patch of the bed 6 nestles, is seen towards the southern end of the map. The beds here, as shown by the arrows, dip on every side inwards towards a centre, and the outcrops run in concentric rings round the central area of the highest member.

This trough is terminated on the south by a half-basin, the simple synclinal lie being exchanged for inclinations to the north-east, north, and north-west, and the outcrops on either side wind round till they meet.

Parallelism of Anticlinals.—It frequently happens that anticlinal ridges show a tendency to run rudely parallel to one another over large areas.

Classes of Anticlinals.—Anticlinals may be distinguished according to their transverse section into three classes, examples of which are seen in Fig. 68, which is a general section after Professor H. D. Rogers, across the Appalachian Mountains.

In the first class the beds on opposite sides are equally inclined to the horizon, and the axis plane is therefore vertical. This symmetrical form is common among gentle undulations of considerable width, such as are seen in the left of the section.

In the second class the beds are more steeply inclined on one side than on the other, so that the axis plane is no longer vertical; foldings of this kind occur in the middle of the section, and it will be noted that in all of them the steeper side of the arch faces the west.

In the third class the rocks are doubled under on the steeper side of the fold, so that the upper beds plunge down on that side beneath those which before disturbance lay below them. The axis plane here is

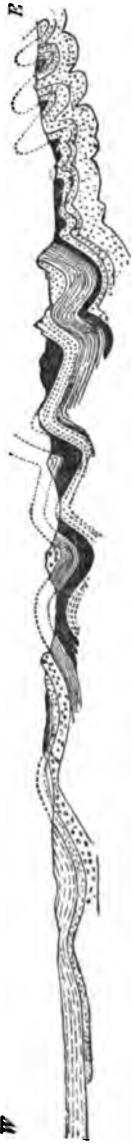

Fig. 68.—General Section across the Appalachians.

inclined to the horizon, but at a smaller angle than the beds on the steep side. This form prevails towards the right hand of the section.

These three forms are seen in the instance before us to pass into one another, and the theory of their formation will be touched on in Chapter XI.

Inversion.—Instances of inversion of the beds, such as that which occurs on the steep side of the anticlinals last mentioned, are not uncommon, specially in intensely contorted mountain regions. A simple case is shown in Fig. 69, which is a section in the neighbourhood of Pembroke. There are three groups of rocks.

3. Carboniferous Limestone. (Top.)
2. Lower Limestone Shale.
1. Old Red Sandstone. (Bottom.)

There is ample evidence in the neighbourhood that, where they have not been disturbed from their original position, the three groups lie one on the other in the order indicated above; and they are found in their normal position on both sides of the synclinal trough on the south. On the north side of the anticlinal arch which follows, however, they have been so completely folded over, that the Old Red Sandstone is at the top and the Limestone Shales and Limestone dip under it, so that an observer who had seen only this end of the section would be led by it to believe that the Old Red was the uppermost and the Limestone the lowest of the three groups, whereas exactly the reverse is the case.

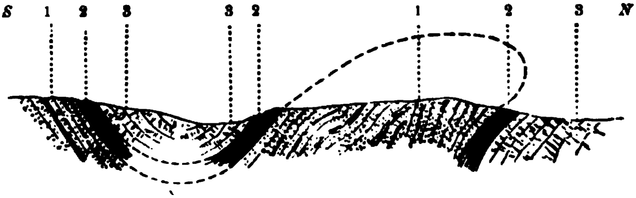

Fig. 69.—INVERTED BEDS NEAR MILFORD HAVEN.
Scale 1¼ inches to a mile.

A case of more violent inversion is shown in Fig. 70, which is a section in the eastern part of the Jura.* The rocks when undisturbed, as at the northern end of the section, occur in the following order:—

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* Copied from Beitraege zur Geol. Karte der Schweiz, vol. iv. For other cases of startling inversion, see Der Glärnisch, ein problem Alpinen Gebrigsbaues, Dr. A. Baultzer. Zurich, 1873.

7. Freshwater Marl. (Top.)
6. Nagelfluh.
5. White Jura Beds.
4. Brown Jura Beds.
3. Lias.
2. Keuper.
1. Muschelkalk. (Bottom.)

On the south a very sharp fold occurs, by which the beds have been thrown over, till the lowest member, the Muschelkalk, has come to lie at the top, and the other subdivisions appear beneath it in an order exactly the reverse of the above table. The reader will realise the enormous amount of displacement and denudation necessary to bring about this result if he will endeavour to put the beds back into the position they must have had before the folding took place. This has been done for a part of the section in Fig. 71, where the letters *A B C* show what was the original position of the points denoted by the corresponding letters in Fig. 70. The five lowest groups must have been to some extent folded and denuded before the formation of the Nagelfluh began, because the latter does not everywhere rest on No. 5, but is at different points in contact with

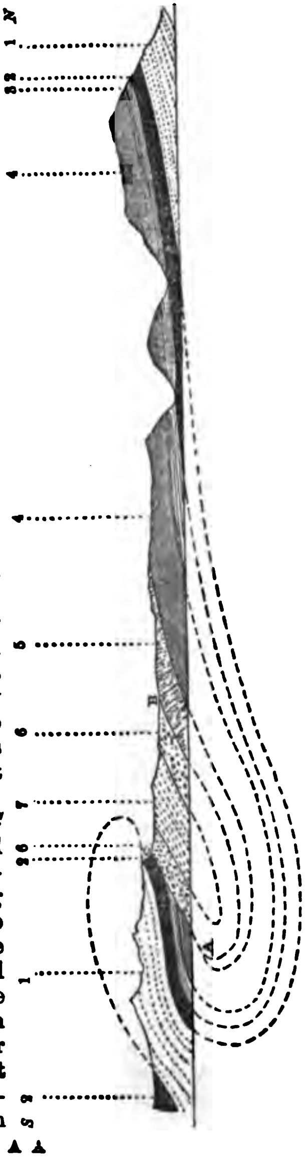

Fig. 70.—Inversion in the Jura.

Nos. 4, 3, and 2. On the surface so formed Nos. 6 and 7 were afterwards laid down in horizontal beds, and Fig. 71 shows what must have been the relative position of the several groups when this step of the process was completed. Then ensued a period of disturbance, by which the contortion and inversion were produced. The nature of the displacement will be more fully seized on if we fix our attention on any one bed singly, say the band of Keuper to the north of *C*. This before disturbance was dipping gently to the north, as in Fig. 71. It must have been gradually tilted till it became vertical, and then actually dragged over so as to make it slope in a direction exactly opposite to that it had to begin with; in fact, the angle through which it has been turned is very nearly two right angles. While this crumpling went on denudation was at work, and by its action all the sheet of Nagelfluh and Marl has been carried away except that portion which is squeezed into the middle of the fold, where it is protected by the beds that have been bent over it.

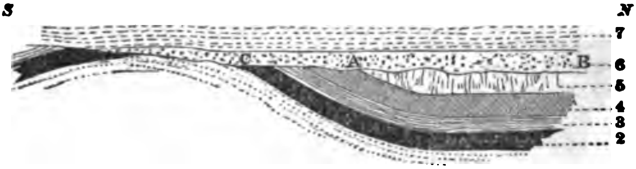

Fig. 71.

When we see these startling results as they are now, they look at first sight almost beyond reasonable explanation; but if we try in imagination to put back the rocks into their original position, to follow them through the successive foldings they have undergone, and bear in mind at the same time how much has been removed by denudation, we are able to realise some at least of the steps of the process, though the forces and the machinery by which the movements were produced may still be beyond our grasp. In Fig. 72, for instance, the dark portion represents a section across a mountain chain, on the flanks of which inversions are repeated over and over again. Cover over with a bit of paper cut to shape the lighter part of the diagram, and see what we could learn about the order of the beds from the darker part, that is from the mountain side as it now stands. Take only two beds, the dotted one and the one marked by a thick black line; at the summit the first overlies the second, a little way down they occur in the reverse order, and still further below they come back to their original relative position; and these changes are again repeated lower down. In such a section no one could say which was top and which was bottom, and the true sequence of the beds could be ascertained only by following them to some district where they are less disturbed.

And if we think only of what we can now actually see, that is, if we still keep the paper covering on, we are puzzled to imagine how this repetition could have been produced. But if we take away the paper cover, we then see how matters stood before the ground had its present shape given to it, and our difficulties are materially lessened. At one time the surface may have been in some such position as *A B*, and the rocks beneath it had been puckered up in a series of zigzag folds. Then out of this block of crumpled strata denudation carried away everything down to the uneven surface *C D*, and so carved out the mountain chain. When we try to make out the structure of such ground we are at first bewildered, because we see only the portions of the folds that have survived; but our difficulties vanish when we complete each fold by restoring the portion which has been carried away, and so are able to understand how what are now isolated portions of each bed were once connected.

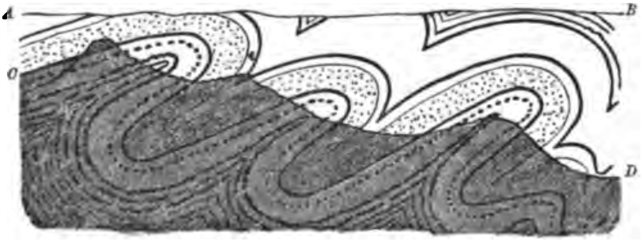

Fig. 72.

We have for distinctness' sake spoken of the folding of the beds and the carving out of the mountain chain as two independent operations, the first of which was finished before the second began. In reality denudation was going on at the same time as the crumpling, but it continued to act after the latter process had come to an end,

Outlier and Inlier.—Tilting and bending, combined with subsequent denudation, have often resulted in the production of isolated patches of rock, and of these there are two kinds, *Outliers* and *Inliers*.

In an outlier the detached mass is surrounded *on all sides* by beds geologically *below it*, in an inlier by beds geologically *above it*.

Instances of outliers are seen in Fig. 65, where three detached patches of the bed No. 5 occur in the northern part of the map, across one of which the section on Fig. 66 is carried. Towards the south end of the same map a larger basin-shaped outlier of the bed No. 6 is seen, which is crossed by the section in Fig. 67.

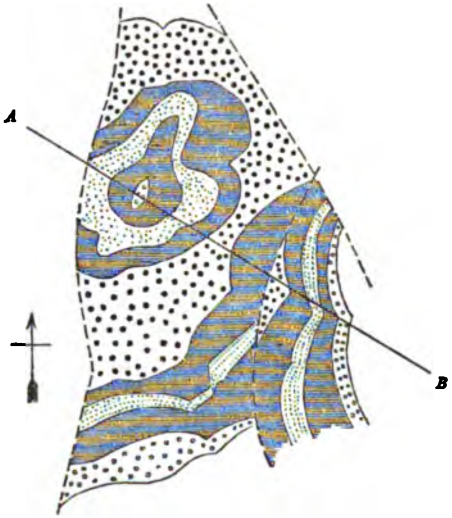

Fig. 73.—Geological Sketch-map of Shutlingslow.

Scale 1 inch to a mile. Dotted lines are faults.]

Again, in Fig. 98, there are two outliers of the bed (*d*) and one of the bed (*b*).

An example of an outlier is given in Figs. 73, 74, and 75, which are a view, sketch-map, and section of a hill called Shutlingslow, a very conspicuous object in the moorlands of North Staffordshire. The outlier, which is formed by the isolated patch of the bed No. 5, is very small, but the rock of which it is composed is a hard massive gritstone, and in consequence of this character it has given to the summit an outline so bold and characteristic, that a trained eye at once recognises from the shape of the peak its general geological structure.

Outliers are the remains of a broad sheet of the rock, which once spread far and wide over the country, but the greater part of which has been carried away by denudation.

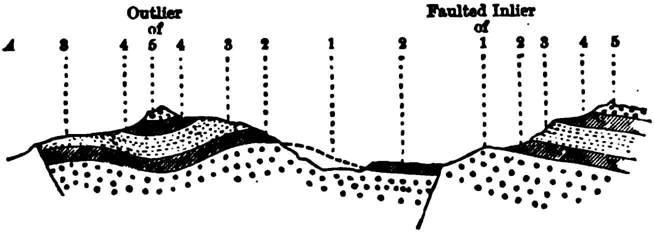

Fig. 74.—Section along the Line *A B* in Fig. 73.

Thus, in Fig. 99, the outlier of the bed (*b*) on the hill to the right must once have been connected with the strip of the same bed which crops out along the flanks of the hill to the left, as shown by the dotted lines; and the bed (*d*), of which only two outliers remain was once equally extensive.

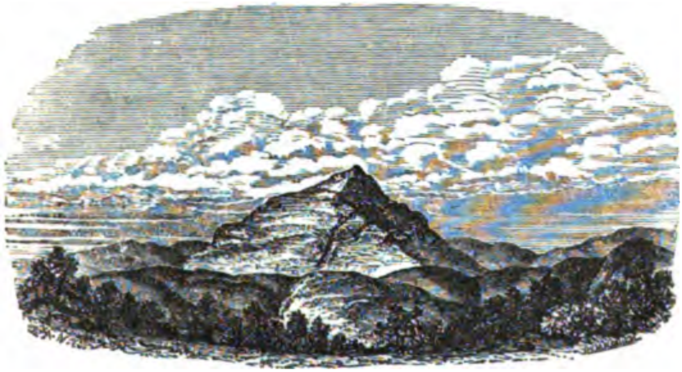

Fig. 75.—View of Shutlingslow

In many cases the dislocations called faults, which will be described in the next section, have contributed to the formation of outliers. Thus in Figs.76 and 77 we have an outlier of the bed No. 5, bounded on the east side by a fault, which has upheaved and brought in contact with it the lower bed No. 1.

Inliers often result when beds have been thrown into a dome, and the upper part of it has been shaved off by denudation. In this way a rounded area of the lowest bed which reaches the surface is laid bare, and the bed next above mantles round it in a ring. Such has been the case in Simon's Seat (see Fig. 62), where an inlier of the bed No. 2 occurs

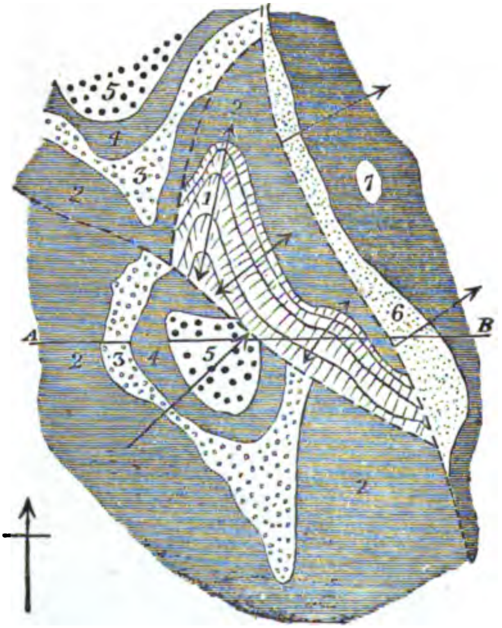

Fig. 76.—Geological Sketch-map of Crich Hill.
Scale 1 inch to a mile. Dotted lines are faults.

at the top of the hill. Inliers of this kind were called by the older geologists "Outliers by Protrusion."

But faults have also had a share in the production of inliers. Thus, in Fig. 73, there is a small triangular area of the bed No. 1, overlaid on the north-east and south-east by the bed next above, and with the same bed brought against it by a fault on the west.

Crich Hill in Derbyshire is a good case of a faulted inlier. Figs. 76 and 77 are a map and section of it. The patch of the bed (1) satisfies the definition of an inlier; on the west and south-west it is bounded by faults, which have let down higher beds against it, while to the north-east it passes with a regular dip beneath the bed (2) immediately above it.

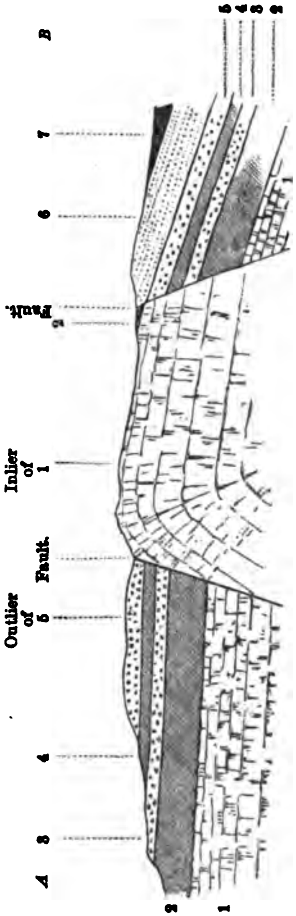

Fig. 77.—Section along the Line *A B* in Fig. 76.

SECTION IV.—FAULTS.

Rocks have been subjected to still more violent usage than the folding we have already spoken of. In many cases they have been torn across by rents, and the parts which were originally continuous now lie at different levels on opposite sides of the fissure.

Such displacements are known as *Faults*. *Throws*, *Troubles*, *Heaves*, *Slips*, and other local names are also applied to them.

Fig. 78 is a section of a group of Coals, Shales, and Sandstones intersected by two faults.

If we look at the fault on the right, we see that the measures on both sides of it are exactly the same in number, thickness, and composition, but that on the left hand they are bodily in a lower position than on the right hand. This fault is said to throw down, or to have a downcast, to the left. Similarly the other fault throws up in the same direction, or down to the right. The amount of the throw, or the size of the fault, is measured by the vertical distance between the ends of the same bed on opposite sides of the dislocation; thus the dotted line *AB* is the throw of the fault to the left in Fig. 78. The throw of faults varies from a few inches up to thousands of feet.

Sometimes beds show little or no change of dip on approaching a fault, as in the section on Fig. 79. This does occasionally happen in the case of faults of considerable size. More frequently, however, the beds are steeply tilted or violently contorted in the neighbourhood of a fault, as in the section on Fig. 80. The amount of contortion does not necessarily bear any relation to the size of the fault, being sometimes very conspicuous where the throw is small.

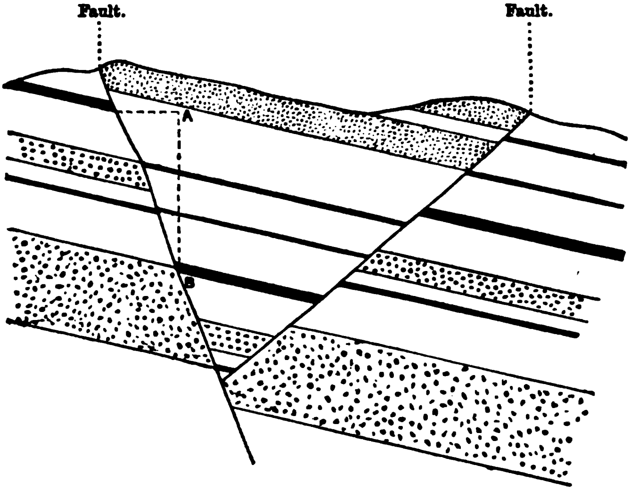

Fig. 78.

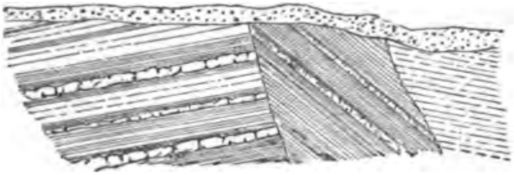

Fig. 79.—Faults unaccompanied by Disturbance or Contortion.

A fault is sometimes a single clean cut fracture, but it oftener happens that, as we draw near a large fault, the beds are broken by a number of smaller dislocations, as in the section on Fig. 81 where we cross several such before reaching the main fault. These minor throws are frequently parallel to the main fracture. In other cases faults branch off at large angles from a main throw, and decrease rapidly in size as they recede from it till they die out altogether. Fig. 82 is a ground plan of a main fault and a group of associated smaller faults, some of which are rudely parallel to the principal dislocation, and others branch off from it at various angles, while all show considerable changes in the amount of throw.

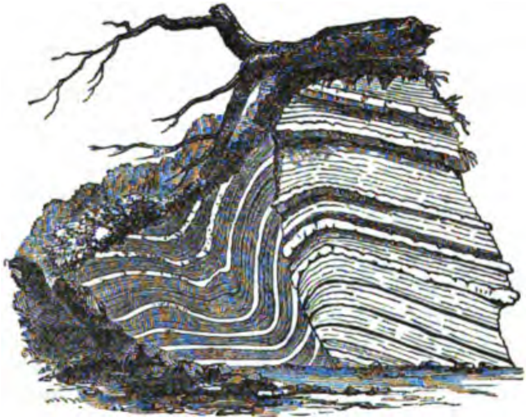

Fig. 80.—Contorted Beds in the Neighbourhood of a Fault.

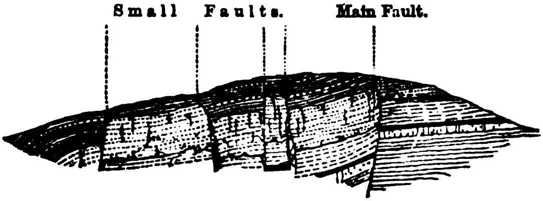

Fig. 81.

The fissure of a fault is now and then narrow, clean cut, and of a uniform width. It oftener happens, however, that the walls of a fault are uneven, alternately approaching and receding from one another. The spaces thus formed are filled up with fragments of the adjoining rocks, mashed and jumbled together, in some cases bound into a solid mass called "fault-stuff," or "fault-rock." Where a fault traverses clayey rocks, its fissure is often lined by a layer of extremely dense, tough, leathery fault-stuff, called in some districts a "leather coat." Now and then a fault is filled in with crystallised minerals; and if among them metallic ores occur, it becomes a mineral vein.

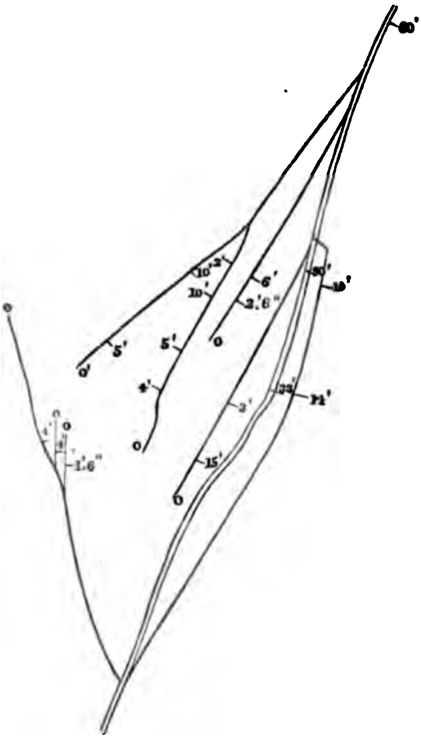

Fig. 82.

Ground plan of a main fault with branches and parallel faults. Main fault shown by a double line, other faults by single lines. Each fault has a small cross-mark placed on the down-cast side, and the amount of the throw written alongside in feet and inches. A cypher is placed where a fault dies out.

Slickenside.—The walls of a fault are frequently grooved and sometimes highly polished, as if the rocks on opposite sides had ground against one another. Such markings are called *Slickensides.* In many cases they are undoubtedly due to the cause just mentioned, and it often looks as if the heat produced by the friction had baked and hardened the rock, and coated the walls of the fissure with a glazed lining; in other cases a thin glaze of some mineral seems to have been deposited on the polished surface increasing its smoothness.* Surfaces marked by slickenside are often found traversing beds in every direction in the neighbourhood of a fault, as if the whole body of the rock had been shattered and the bits rubbed against one another by the motion which produced the displacement.

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* See Journal of Royal Geol. Soc. of Dublin, x. p. 96. See also Quart. Journ. Geol. Soc. xxxi. 111, 113, 386.

Cases also occur where inclined beds have slipped upon one another and marked their faces with slickenside, and we may even see the faces of joints traversed by horizontal polished grooves, such as would be produced by horizontal motion and grinding.

On approaching a fault some rocks, especially Sandstone, lose their bedding and become shattered and traversed by a number of cracks roughly parallel to the plane of the fault, which are sometimes called "Ruttles" by quarrymen. Such changes, which are perhaps akin to cleavage, and the hardening often noticed adjoining a fault, point to pressure and other violent treatment during the production of the dislocation.

Hade of Faults.—Faults are sometimes vertical, but by far the larger number are inclined at different angles to the horizon. The inclination of a fault is called its *hade* or *underlie*, and is measured by the angle between a vertical plane and the plane of the fault.

In almost all cases of inclined faults *the hade or slope is towards the down-throw side:* exceptions to this rule are called "reversed faults." Cases of reversal are occasionally seen, but many of them are probably more apparent than real, and caused by some temporary bend in the direction of the fissure. I have seen such a case, where the fault, on entering a well-jointed bed, took the line of a joint with an opposite slope to its own, and so became for a short part of its course reversed, while if looked at as a whole it followed the general law.

Genuine reversed faults are, however, said to occur in highly contorted districts.*

Course of Faults.—The course of a fault is rarely, if ever, absolutely straight, but in the majority of cases faults show a tendency to run in straight lines; sometimes the deviations from a straight line are so small as to be scarcely noticeable, and in many cases, where they are quite sensible, there is still a general tendency to a rectilinear trend, the fault swinging first to one side and then to the other of a straight line which represents its average direction. The bendings in such a case are usually gentle curves, but occasionally very abrupt zigzags.[*] Some faults, on the other hand, are decidedly curved.

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* See Prof. H. D. Rogers, Transactions Royal Soc. of Edinburgh, xxi. p. 443.

Parallelism of Faults.—It frequently happens that the faults of a district can be divided into two systems, and that all the members of one system show a general tendency to run parallel to the strike, while those of the other system range roughly along the dip. The faults of the first system will be parallel to the longer axes of the larger folds in the rocks, and thus faulting and folding seem to stand in close connection, and to be only different results of the same process. A relationship between faults and anticlinals is also pointed out by the fact that the one sometimes pass into the other. The sharpness of the bend gradually increases, till at last the tension became greater than the rock could stand, and fracture accompanied by relative displacement of the severed portions resulted.[†]

Changes in Size and Dying out of Faults.—The amount of the throw of a fault very seldom keeps the same value for any long distance, and we will glance at some of the causes which produce changes in the size of faults.

If a fault be perpendicular to the strike, its throw will remain the same as long as the beds on opposite sides of it have the same dip and strike.

Changes, however, in the amount or direction of the dip will give rise to corresponding changes in the amount, and in certain cases in the direction, of the throw. Fig. 83 shows a model which illustrates one way in which this is brought about. There is a bed of Coal shown by the thick black band, shifted by a fault *A B C D*. The measures overlying the Coal are supposed to be removed so that we see its surface. On the north side of the fault the bed dips steadily to the east, and its surface is the plane *B C E F*. On the south side the bed has been thrown into a series of folds giving it a wavy surface, *A L K H G M N O*. Between *C* and *G* the bed is lower on the south than on the north side, or the downthrow is to the south. The amount of throw, however, steadily decreases as we go towards *G*, and at that point the bed is at the same level on both sides of the fault, or the fault has no throw. Between *G* and *H* the bed is higher on the south than on the north side, or the fault throws down to the north. The amount of the throw increases to the west of *G* for a while, then begins to decrease, and at *H* again comes down to nothing. Between *H* and *K* the fault resumes its former southerly downthrow, and at *L* another change in the direction of the throw occurs.

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[*] See a very jagged faulted boundary of the Carboniferous Limestone on Sheet 81, S.E. of the one-inch map of the Geological Survey of England and Wales, and its description in the Memoir of the Geological Survey on North Derbyshire and the adjoining parts of Yorkshire, p. 33.

[†] The Rivelin Valley, near Sheffield, furnishes an instance. See Memoir of the Geological Survey of England on North Derbyshire and the adjoining parts of Yorkshire, p. 67; also Geological Magazine, vi. 507.

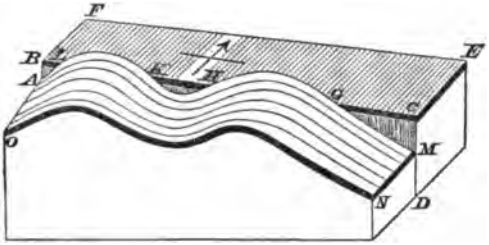

Fig. 83.—Changes in the Amount and Direction of the Throw of a Fault, produced by Change of Dip.

The same result will evidently be produced when there are a number of branch faults springing out from a main fault.

In the model in Fig. 84, the measures overlying the black bed are, as in the last figure, supposed to be removed.

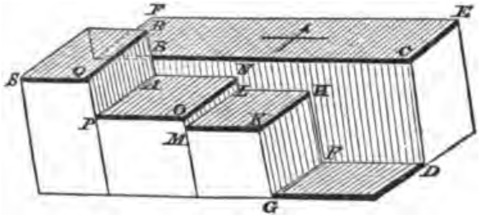

Fig. 84.—Changes in the Amount and Direction of the Throw of a Fault, produced by Branch Faults.

A B C D is the plane of a fault, and *B C E F* the surface of the bed on the north side of it. At *C* this fault throws down 100 yards to the south, so that on the latter side the Coal is found in the position *D F G*. *F G H K* is the plane of a branch fault throwing down to the east 80 yards; this fault does not affect the bed on the north side of the main fault, but on the south side the bed is brought by it into the position *K H L M;* there is now only 20 yards difference in the position of the bed on opposite sides of the main fault, or the throw of the latter is reduced to 20 yards. Still further to the west is another fault, *L M N O*, throwing up 10 yards to the west, and bringing down the size of the main fault to 10 yards. Lastly, the branch fault, *P O R B*, throws up 40 yards to the west; by this fault the Coal is raised up to *Q R S*, and is 30 yards higher on the south than on the north side of the main fault, or the throw of the latter is now 30 yards down north.

In this way by a succession of steps a fault which throws down to the south 100 yards is changed into a fault with a downthrow to the north of 30 yards.

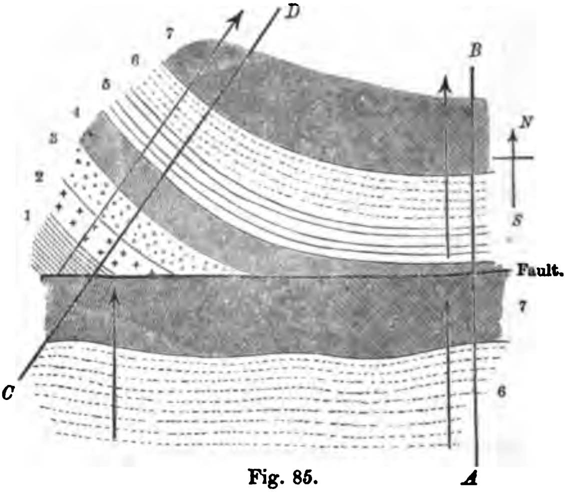

Fig. 85.

It is easy to see that by proper adjustments a fault might be made to die out permanently in cases such as those just described. In Fig. 83, suppose that the bed on the south side of the fault, instead of rising to the west of *K* at as steep an angle as in the figure, took the same inclination as it has on the north side. The bed would then be at *K*, and would continue to be to the west of *K*, at exactly the same level on both sides of the plane *A B C D*, or the fault would disappear. The same result would be brought about in Fig. 84, if the throw of the fault *A P Q R* was 10 yards.

Mining operations constantly afford proofs of the dying out of faults, and this must be brought about in some such manner as has been described. Frequently a large fault splits up near its termination into a number of branches, each of which gradually dies away.

If the beds have a different strike on opposite sides of a fault, and the line of the latter is parallel to the strike on one side, its throw will necessarily vary in size.

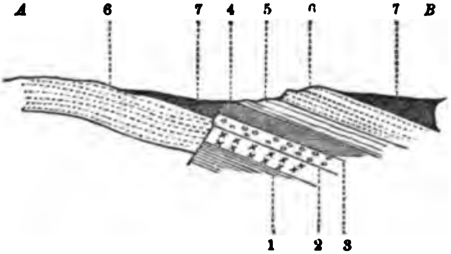

Fig. 86.—Section along the Line *A B* in Fig. 85.

For instance, in the ground plan in Fig. 85 we have on the south side of the fault a persistent easterly strike and a dip to the north; on the north of the fault the strike gradually changes from an easterly direction on the one side to a north-westerly trend on the other. The fault runs east and west, or parallel to the strike of the beds on its south side. The consequence is, that, as we go to the west, we find the bed 7 brought against lower and lower members of the series, or the downthrow of the fault increases. The increase in size will be evident from comparing the two sections *A B* and *C D;* in the first the bed 7 is brought on a level with the bed 3, in the second it has been still further let down so that it is on a level with the lower bed 1. It is worth notice that if we had confined our investigations to the neighbourhood of the

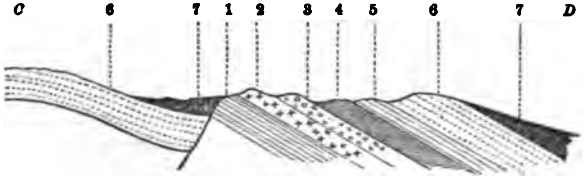

Fig. 87.—Section along the Line *C D* in Fig. 85.

line *A B*, where the beds have the same strike on both sides of the fault. and the latter ranges along the strike, we should not have detected the existence of the beds 3, 2, and 1; and unless the fault had been actually seen, we might not have become aware of its existence, and might have supposed the beds on its south side passed under 4, instead of really lying a long way above that bed.

Effect of Faults on Outcrop.—It is very important that the practical geologist should clearly realise the effect which faults have in shifting the outcrop of a bed.

In Fig. 88, *A B C D E* is the surface of the ground, supposed, for simplicity's sake, horizontal; *G E L H*, the plane of a fault; *D E L F*, *A K H G*, the position of the same bed on opposite sides of the fault, the measures overlying the bed being supposed to have been removed. *E D*, the intersection of the bed with the surface on the upcast side of the fault, shows its outcrop on that side; but it is clear that after having been thrown down into the position *A G H K* it will not reach the surface till some way to the left of *E D*, such as at *A G*. That is to say, *on the downcast side the outcrop is shifted towards the rise.*

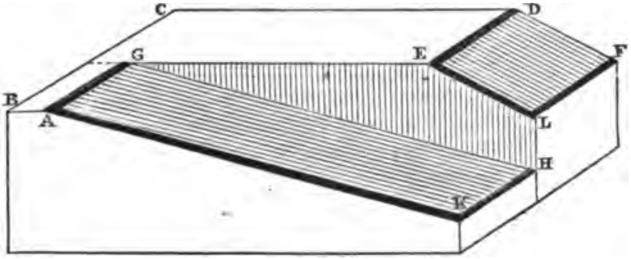

Fig. 88.—Shifting of the Outcrop of a Bed by a Fault.

If we knew the angle of the dip, it is evident that, by measuring the horizontal displacement *G E*, we could calculate the vertical throw of the fault. The smaller the dip the greater will be the amount of the shift, and the only case in which the outcrop will not be shifted is when the beds are absolutely vertical.

If the surface of the ground be undulating, the displacements of the outcrop will become more complicated; but the above rule will always hold good except when the ground slopes in the same direction as the beds dip and at a larger angle, when the horizontal shifting of the outcrop will be *towards the dip.*

Miners use the term "heave" to describe the horizontal displacement of an outcrop by a fault. Faults will heave not only beds but any other divisional planes traversing the rocks; thus, if faults themselves have been formed at different times and cross one another, the one last produced will heave all of earlier date which are not absolutely vertical. Mineral veins are "heaved" in a similar manner.

It is, perhaps, in the case of a group of mineral veins that the effect of a "heave" becomes most conspicuous. The whole of the rocks of a district appear in such a case to have been bodily shifted in a horizontal direction. But the reasoning just gone through shows that there need not have been any horizontal motion whatever, and that the shift may be due to a displacement which was entirely vertical. If we know the amount of the vertical throw and the dip of the heaved bed or vein, we can calculate the amount of horizontal shift that would result; and if the observed shift agrees with the calculated displacement, the throw of the fault must have been altogether in a vertical direction. But it must not be assumed that the displacements produced by faults are always wholly vertical; it is conceivable, nay, highly probable in those cases where the rocks have been subjected to powerful horizontal compression, that horizontal motion may have taken place, and that beds may have been moved not only up and down, but also to and fro on opposite sides of a fault.

Indirect Evidence for Faults.—We have sometimes the good luck to see faults in actual section, as in Figs. 79, 80, and 81, which are all sketches from nature. But in many cases the geologist has to infer the presence of faults from circumstances connected with the lie of the beds which cannot be explained any other way.

Thus the shifting of the outcrop of a bed is proof positive of a fault; and by noting where the outcrops of successive beds are broken and heaved, we get a series of points on the fault, and can lay down its line.

There is another way in which we are often enabled to infer the presence of a fault that is nowhere actually seen, which will be understood by a reference to Fig. 85. In the district of which that woodcut is a geological map, the group of beds numbered 1 to 5 run up one after the other to the outcrop of the bed 7, and end off against it. Now this abrupt termination of the outcrops of the beds 1 to 5 may be produced in two ways: there may be a fault, as is actually the case in the instance before us, ranging along the line where the outcrops are stopped off; or there may be between the group 1 to 5 and the bed 7, what is known as an unconformity, the meaning of which term will be explained in Section VI. of the present chapter. But if we are sure there is no unconformity, then such behaviour of the outcrops as is shown in the figure can be explained in no other way than by a fault.

We may also infer the presence of faults in cases such as the following, and, if we take due care, our conclusions may be as safely relied upon as if we had actually seen the fault itself. If from a study of sections we establish the fact that a certain bed, *A*, is always found beneath another bed, *B*, and then find at any spot *A* dipping so as to abut against or pass over *B*, and *if by no possible contortion or inversion B could be got to pass under A*, then there must be a fault between them.

Figs. 89 and 90 will illustrate the line of reasoning pursued in such cases. If we go northwards from Filey Brig along the Yorkshire coast, we find a beautiful series of sections in the cliffs, which show beds coming out one from under the other in the following order:—

4. Sandy Limestone and Calcareous Sandstone. Coralline Oolite.
3. Blue Sandy Clay. Oxford Clay.
2. Calcareous Sandstone. Kelloway Rock.
1. Sandstones and Shales.

We follow the lowest division, and find it forming a series of headlands seen in the most distant parts of the view, and after passing these we enter the southern part of Cayton Bay, a sketch of which seen from the north is given in Fig. 89. The darkly-coloured promontories about the middle of the coast line are formed of the Sandstones (1); then comes a portion of the cliff more moundy in outline, where a thick mass of stony Clay descends to the sea-level and hides the bedded rocks from view. Between this obscure ground and the spectator rise the bold Lebberston Cliffs, which we recognise at a glance to be composed of our old acquaintances Coralline Oolite, Oxford Clay, and Kelloway Rock.*

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* In the sketch the first is left nearly white, the Oxford Clay light with streaks of bedding, and a dark bed of Kelloway Rock sticks out at the bottom.

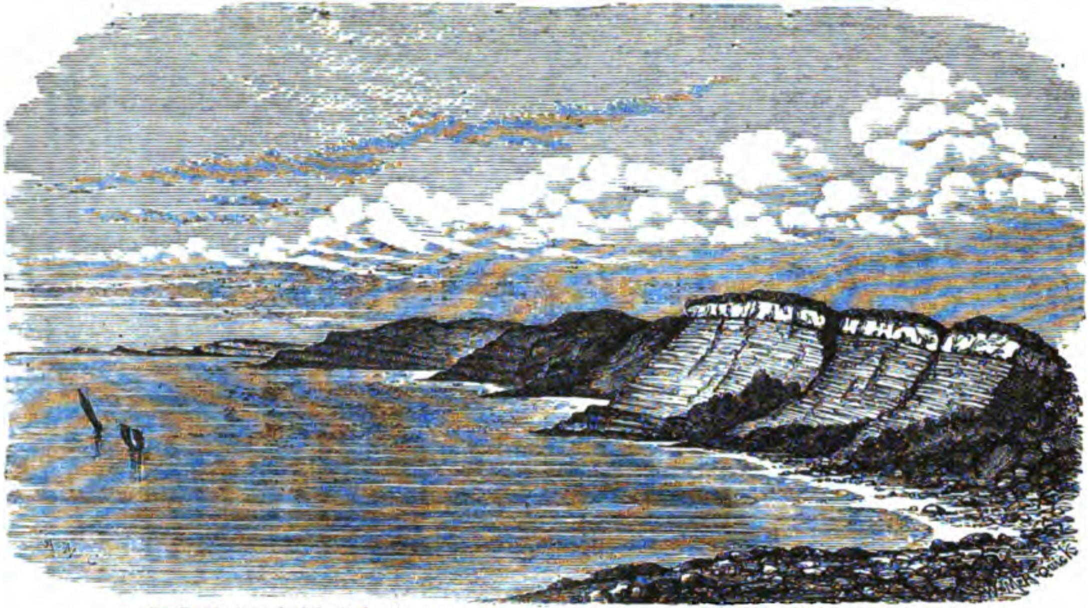
Headlands formed of the Beds (1).
Lebberston Cliff.

Fig. 89.—View of Cayton Bay, near Scarborough, looking South: showing indirect Evidence for a Fault.

The dip is quite perceptible even from a distance; and if we carry on the lines of bedding in the headlands beyond the clay-covered interval up to Lebberston Cliff, we see that, so far from the Sandstones of the former passing beneath the Kelloway Rock of the latter, as we found was the case in the normal unbroken section to the south, they would, if they retained the same dip, abut against the Oxford Clay. The first question we ask ourselves is, whether the Sandstones may not bend over rapidly to the north beneath the clay-covered ground, then resume their old dip, and so come into their proper position beneath Lebberston Cliff? But we can detect no symptoms of the abrupt changes of dip required by this supposition, and, what is more, when we test the idea by actual measurement, we find that *by no bending however abrupt could the whole thickness of the group* (1) *be got in between the points where the clean-cut sections on the north and south terminate.*

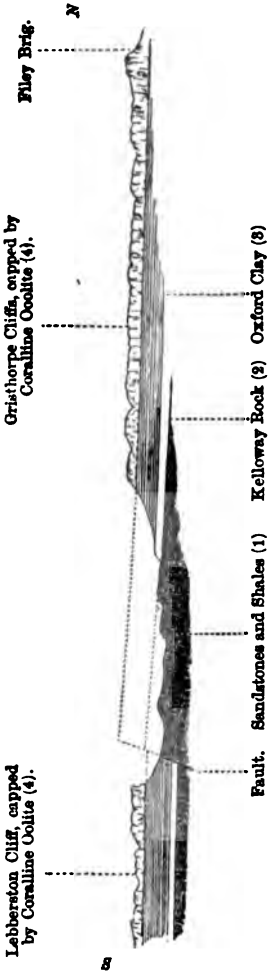
N
Filey Brig.
Gristhorpe Cliffs, capped by Coralline Oolite (4).
Lebberston Cliff, capped by Coralline Oolite (4).
S
Fault. Sandstones and Shales (1) Kelloway Rock (2) Oxford Clay (3)

Fig. 90.—Section from Lebberston Cliff to Filey Brig.

One explanation alone remains, namely, that the rocks of Lebberston Cliff have been let down against the Sandstones by a fault, and we accordingly construct our section as in Fig. 90,* and restoring by the dotted lines the parts which have been carried away by denudation, we find that the fault brings the base of the Kelloway Rock just on a level with that of the Coralline Oolite, or that its throw is equal to the combined thickness of the Oxford Clay and Kelloway Rock.

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* It will be observed that the deep hollow on the section to the south of Lebberston Cliff does not exist in the view. It is filled up by the stony Clay already mentioned, which caps all the distant cliffs, but is omitted in the section to avoid confusion.

Evidence as complete as that just given may be always safely accepted as unquestionable proof of faulting; but the observer must be on his guard against jumping too hastily to conclusions in such cases, and must not call in a fault to help him out of a difficulty till he has thoroughly satisfied himself that the relative position of the beds can be explained in no other way. Where a fault is only one way out of several of explaining observed facts, it may yet be the best way and its presence highly probable; but the observer must endeavour to obtain additional evidence sufficient to put the question beyond reasonable doubt before adopting a fault as the final solution.

SECTION V.—HOW THE DISPLACEMENTS OF THE ROCKS WERE PRODUCED.

Such is an outline of the displacements which rocks have undergone. We may next inquire how they were produced, and this inquiry naturally falls under two heads.* The first is purely geometrical, and asks what was the kind of motion by which they were brought about? The second is mechanical, and inquires what were the forces that caused that motion? The first question may be treated of here, the second falls to be considered in part in Chapter XI.

Character of the Movements.—It is evident that the movements to which uplifting and tilting were due cannot have gone on everywhere to the same extent. Rocks have been raised higher and more violently disturbed at some spots than at others. The next question is, was the disturbance sudden, and confined to certain lines or centres, so that the rocks were snapped and raised at a bound into the positions they now occupy? Or was the displacement widespread, and varying continuously in amount from place to place, so that it reached a maximum along certain lines or around certain centres, and died away gradually as it receded from them?

Experience is against the first supposition; for, although there are instances of sudden and local upheaval produced by earthquakes, by far the larger number of the cases of oscillation that have been observed extend over large areas, and vary in amount and direction continuously.

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* Corresponding to the two subdivisions of the mechanics of motion, Kinematics and Dynamics, or the science of motion and the science of force.

What is more, connected observations of the lie of rocks over a large area furnish evidence of the strongest kind in favour of the second supposition. Isolated measurements show us beds dipping here in one direction at one angle, and there in another direction at another angle. Now, suppose that, when we have amassed a sufficient number of such observations, we endeavour to determine from them what must be the underground course of the rocks in order that they may come out at each spot where they are seen with the observed dip and direction, and so to arrive at a general view of the geological structure of a country. Whenever we do this, we find that we can account for the observed facts only on one supposition, and that is, that *the rocks have been folded into a series of troughs and arches, or thrown into domes and basins.* This is the great general law which governs everywhere the arrangement of the disturbed portions of the earth's crust.

Faulting, or violent contortion and inversion, often complicate and obscure this structure and interfere with its symmetry, but never to such an extent as to prevent its being recognised as the great leading feature in the arrangement of the rocks. Disturbances such as these last are therefore of the nature of accidents, and if we eliminate them, and try to form a broad general view of the lie of the beds under a large area, it is the structure just mentioned that invariably comes out.*

We may say, then, that wherever we find beds inclined to the horizon, we are somewhere on the slope of an anticlinal; and wherever the beds of a rock group that has undergone disturbance lie flat, we are on the crest of an anticlinal, or at the bottom of a synclinal, or on one of the horizontal portions of the minor bendings that are ever occurring here and there in the sweep of the grand curves.

Whatever may have been the forces to which this arrangement has been due, it is quite evident that the movement which produced it cannot have been local, but must have prevailed as universally as the folding itself;

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* It is hardly possible for any one, who has not gone through a course of practical geological work in the field, to realise fully the grounds on which this assertion is based; but every geologist of experience soon comes to find out the truth of it.

and the generally regular character of the result shuts out completely the idea of a violent, convulsive action, though faulting and contortion point to concentration of energy around the spots where they occur.

All the observed facts, therefore, are decidedly in the teeth of the first solution, and strongly in favour of the second.

Folding would produce both Elevation and Dip.—Folding such as we have described, of course, necessarily involves tilting, and all the different forms of inclination which have been described as occurring in nature. And it is clear that it would also produce both elevation and depression, the one when portions of the earth's crust are carried aloft on the summits of arches, the other when portions are sunk into troughs; and it is highly probable that the great leading physical features of the globe were in the first instance marked out by movements of this character—that mountain chains follow lines of sharp crumpling, continental areas repose on the summits of broad arches, and oceanic depressions run along wide troughs.* But the reader must not jump to the conclusion that all hill ranges coincide with anticlinals and all valleys with synclinals. We shall see in the next chapter that in most cases the reverse of this is true, and that the present surface of the ground is largely due to denudation—acting while the folding was going on, or after it was finished—which has immensely modified the forms that would have resulted from elevation alone.

Direction of the Folding Force.—Our next inquiry is, in what direction did the force act which brought about the foldings and displacements that have been described in the preceding pages?

There are two perfectly distinct methods by which these results might be produced. The very word elevation suggests the notion of a force that acted *from below vertically upwards*. In order to produce folds all that is necessary is that this force should not act with equal intensity over the area affected by it. Along anticlinal lines it must be at a maximum, and it must gradually decrease in intensity from there down to each synclinal line, along which it must have its least value. The way in which an action of this sort would produce elevation and folding is shown in Fig. 91.

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* Some objections to the last two statements will be noticed in Chapter XI.

Let *P Q* be the surface of an undisturbed bed, and let a force tending to raise the bed vertically upwards be exerted from beneath in the direction of the arrows; let *A* and *B* be points where the force has maximum value, *C* an intermediate point where it is at a minimum. Then, while *A* and *B* are raised to *a* and *b*, *C* will only reach to a less height, *c*, the points *P A C B Q*, will be lifted into some such positions as *p a c b q*, and two anticlinals with a synclinal between them will be formed.

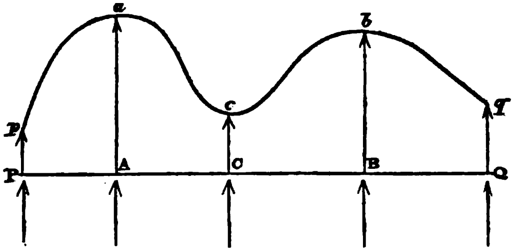

Fig. 91.—Folding produced by Vertical Up-thrust.

But all the results we have been considering might also be equally well produced in the following way.

Suppose the bed *A B* to be subjected to a *horizontal thrust* acting in the direction of the arrows in Fig. 92. The effect would manifestly be to crumple it up into the shape *a c d e b*, and we should again get a series of anticlinals and synclinals.

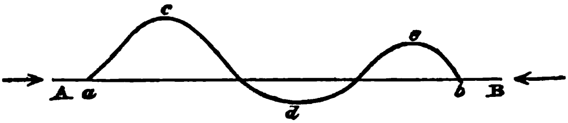

Fig. 92.—Folding produced by Horizontal Thrust.

We have to choose, then, between these two explanations, and to adopt as the most probable the one which accounts for the greatest number of observed facts.

Now as far as the formation of symmetrical arches and troughs, like those in Fig. 91, goes, one way is as good as the other; but when we come to anticlinals where the rocks are doubled under on the steeper side, to complicated contortions and puckerings, and to the inversions which are their results, vertical upheaval is manifestly quite unable to produce these, while on the other hand they are just the forms that would result from lateral thrust. It is impossible, for instance, that the arrangement of the beds in the section across the Appalachians in Fig. 68 could have been brought about by a force acting vertically upwards. There, not only are some of the arches unsymmetrical and some tilted over, but in the first the steepest sides all face the same way, towards the west, and in the second the tilt has been in every case in the same direction. We also notice that the sharpest bends are at the eastern end, and that the folding grows gradually less sudden, and the curves open out as we go towards the west. These are just the results that would follow if a group of horizontal strata were crumpled up by a powerful thrust which acted from east to west.*

At the east end of the section, then, there can hardly be a doubt that horizontal pressure and not vertical upheaval has been the producing cause; and there is such a gradual passage from the violent disturbances of that end into the more symmetrical folds of the western end, that we must admit that whatever caused the one must also have produced the other.

Evidence like this—and similar cases might be brought forward without number—is strongly in favour of the second explanation.

Another test that readily suggests itself is this. In Fig. 91 the bed *A B* must be *pulled out* to bring it into the position *a c b*; in Fig. 92 it must be *compressed*. If, then, we have any means of learning whether folded strata have been *stretched* or *compressed*, we shall make some way towards deciding between the rival hypotheses.

We may first consider whether the amount of stretching required by the hypothesis of vertical upheaval is such as we can reasonably suppose rocks capable of.

In the case of broad open arches and basins perhaps no difficulty would arise on this ground;† but where rocks have been sharply bent into folds which follow one another in rapid succession, they would have to be pulled out to many times their original length to bring them into their present shape. Even supposing rocks as extensible as india-rubber, increase in length must be attended by a corresponding decrease in thickness, and therefore a group of rocks, when sharply folded, ought to appear to be more thinly bedded than in their undisturbed position. But if we take a group of rocks which lie undisturbed at one spot, and are violently contorted at another, we do not find the beds thinner at the latter than at the former. In reality, however, rocks are only slightly extensible, and it is utterly out of the question to suppose that they could possibly have been dragged out to the extent necessary to bring them into their present form by vertical upthrust.*

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* Silliman's Journ., 1st series, xlix. 284.

† The reader will realise how very slight is the curvature of broad basins and arches by consulting section drawn to a true scale across districts where they occur, such as Horizontal Sections, Sheets 77 and 79 of the Geological Survey of England and Wales.

No such difficulty accompanies the squeezing hypothesis: a band of rock, which when horizontal was, say, a mile long, is forced to occupy a smaller space, say, three-quarters of a mile, and the only way in which this could be done is by puckering it up into folds.

Again, the phenomena of cleavage go altogether in favour of lateral thrust. All cleaved rocks are strongly contorted, and the planes of cleavage are parallel to the longer axes of the great folds. Now the structure of cleaved rocks gives proof positive that they have been compressed in a direction perpendicular to the cleavage planes, or, what is the same thing, to the axes of the folds. Lateral pressure therefore has acted on cleaved rocks, *and it has acted exactly in the right direction to produce the existing folds.* When we see that the rocks have been folded, and when we know that they have been acted on by a force competent to produce that folding, we cannot refuse to believe that the one has been the cause of the other. In the case of cleaved rocks, then, it is as nearly as can be a certainty that they were bent into their present form by lateral pressure.

The late Mr. W. Hopkins was one of the ablest supporters of the vertical upheaval theory, and his papers† on the subject are still well worthy the attention of the student of Dynamical Geology, though many of the geological opinions which he held have been long since given up. He tried to get over the objections stated in the last few pages by pointing out how contortion, and faults as well, might result from vertical upthrust. He supposed the uplifted area to be acted on underneath by a force, such as would be produced by the expansion of a body of highly heated elastic vapour, and determined by mathematical calculation what would be the direction of the rents formed, when the rock was stretched up to the breaking point, and fissuring took place. He found that in a rectangular area two sets of parallel fissures would be produced, and that the common direction of one set would be perpendicular to that of the other set.

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* See a very ingenious paper, on the stretching which has taken place in disturbed rocks, by Mr. R. L. Jack, Geological Magazine, viii. 388.

† Researches in Physical Geology, Cambridge Phil. Transactions, 1835; Report on Earthquakes and Elevation, British Association, 1847.

Now suppose *A B C D*, Fig. 93 to be a cross section of one of the arches which has been fractured along the lines *E F*, *G H*, *K L*, *M N*; then the pressure on these parts, such as *G H L K*, which are broadest below, would be greater than in such as *E F G H*; the former would therefore be driven upwards, the fractured portions would be forced into some such positions as in Fig. 94, and faults would be produced *with a hade to the downthrow side*, as is the general rule in nature. The same result would follow if elevation went on till the cracks gaped; for then it would be the wedges, such as *E F G H*, which have their narrowest ends downwards, that would sink. As far as faults go, then, the explanation will do well enough, and Mr. Hopkins has pointed out that, at a future stage of the process, contortion as well might be produced in the following manner:—Suppose that, when the rocks had come into the position shown in Fig. 94, the elevating force ceased to act, and the shattered mass settled down; a horizontal thrust would then be produced, which would increase indefinitely as the arch flattened. The broken portions would be jammed against one another and their beds crumpled up and contorted; it might also well happen that a wedge like *E F G H* would be forced *upwards*

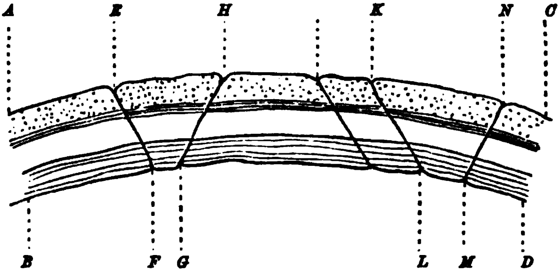

Fig. 93.

by the nip of the two adjoining masses, and in this way *reversed faults*, such as accompany violent contortion, might result.

In this way faults might be produced, and their direction and hade would be the same as in existing faults. Some degree of contortion might also be brought about. But the machinery would hardly be able to effect the amount of widespread and complicated contortion so frequently met with, specially in mountainous districts,* nor to produce cleavage over areas hundreds of square miles in extent. We can scarcely conceive portions of the earth's crust, large enough to produce these results, being tilted bodily over in the manner this explanation requires. In fact, while Mr. Hopkins has clearly realised that contortion involves horizontal thrust, the means he proposes for generating that thrust seem inadequate to produce it over areas sufficiently large.

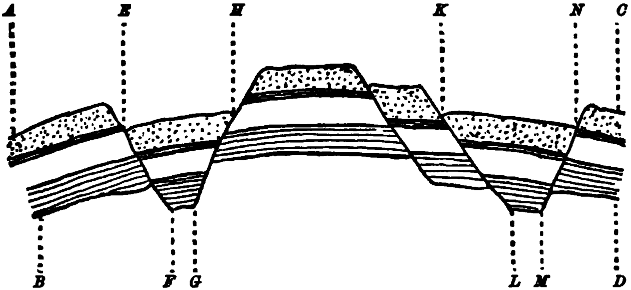

Fig. 94.

Faults then might follow from vertical upthrust; it is not so easy to see how they would be produced by compression. Pressure would, it seems at first sight, have a tendency to close up any rents that existed rather than to open new ones; and even supposing fissures were produced and the rocks on opposite sides of them displaced, the motion would be in such a direction that a "reversed" fault would be produced. For let *A C B a c b* (Fig. 95) be an arched stratum traversed by a fissure, *D C*, *P* the direction of the crumpling force; then it is clear that, if P is approximately horizontal, its resolved component parallel to $C\,D$ will tend upwards from D to C, and the portion $A\ C\ c\ a$ will be pushed up, a displacement which would give rise to a reversed fault.

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* Somewhat similar objections apply to an explanation put forward by Mr. Wilson in the Geol. Magazine, v. 207; his figures show that his method would not produce crumpling enough. Mr. Wilson's explanation of the cause of faults is substantially the same as that given above.

It certainly looks as if stretching were necessary for the production of fissures, and as if the law, that a fault always hades towards the downcast side, could only be accounted for on the supposition that the depressed rocks had slid *down the incline* of the fissure. But the great weight of evidence against vertical upheaval prevents our accepting that as the cause of the stretching.

And stretching would in the end result from lateral pressure if the process were carried far enough. As long as the length of the arc $A\ C\ B$ did not exceed that of the bed in its unbent state there would be no stretching; but as the underlying rocks were gradually arched up into the space $a\ c\ b$, they might prevent the points a and b approaching one another, and still tend to drive the crest of the arch higher up, and their upward motion could go on only by means of the stretching, and at last rending, of the upper layers of the arch. This would give fissures, and we may imagine in a vague sort of way that the severed portions of the arch might get displaced relatively to one another in various ways. The displacement might be due to lateral pressure, in which case we have seen the faults would be reversed; it might be due to portions being forced up by the upward motion of the interior of the arch, in which case there seems no reason why the hade should be towards one side rather than the other; again, at a considerable depth the pressure would probably heat the rocks till they became plastic or half melted, and portions of the shattered upper

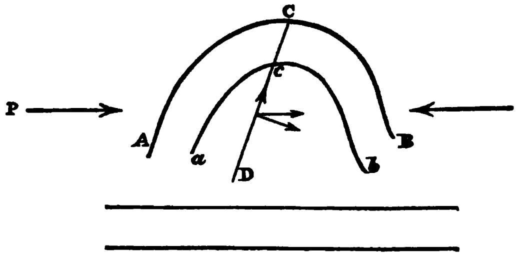

Fig. 95.

part might sink down into the soft bed, in which case the fault would have the normal hade. It is impossible, however, to delude oneself into the belief that lame and crude explanations like these are satisfactory; probably we have yet very much to learn about faults before we can frame a theory which will account on mechanical principles for their production and the law of their hade.

Summary of the Evidence.—The evidence, then, by which we must decide between vertical upthrust and lateral pressure stands as follows.

Tilting and symmetrical folds would result equally from either. Vertical upheaval is capable of giving rise to faults, and indirectly to some degree of contortion; and in the faults produced in this way the observed law of hade would generally prevail, those faults only being "reversed" which accompany great contortion. But no vertical upheaval could bring about the widespread and excessive crumpling which so constantly presents itself, while this is just the arrangement that would follow from lateral thrust. Further, the amount of stretching required by the hypothesis of vertical upheaval is far greater than can be admitted. Lastly, cleavage furnishes proof that rocks have been subjected to just the very pressure requisite to bend them into the folded forms they have assumed. The only displacements we cannot thoroughly explain by means of compression are faults.

While, therefore, some of the observed facts can be accounted for equally well on either hypothesis, there are many which compression alone could produce; indeed, the only one of which the latter fails to furnish a perfectly satisfactory explanation, is the direction of the hade in a normal fault. The present state of our knowledge, therefore, decidedly tends to make us lean to the side of lateral thrust as the kind of force which has produced the displacements we are considering; and to believe that, since the balance of evidence is so enormously in its favour, increased knowledge will remove the only bar that now exists to its being accepted without hesitation as a full and perfect explanation of the cause of these displacements.

But the problem is far from solved. Numerous weak points in the explanations given will occur to the thoughtful reader; and in truth we can so little realise the conditions under which the process of contortion went on, that the best explanation we can arrive at must necessarily be incomplete in particulars.

What gave rise to lateral thrust is a question that falls to be considered in Chapter XI.

Folding went on at great depths.—A very little reflection will convince us that rocks were not bent into their present shapes near the surface, but that when the process went on they were buried beneath a great thickness of strata, which has since been carried away by denudation.

In the first place we have positive proof that all folded rocks have suffered largely from denudation. The arches are never complete, but truncated by the removal of portions of the upper beds. Almost any of the sections in this chapter show this, and in Figs. 99 and 105, the missing parts are some of them indicated by dotted lines. Faults tell the same tale; their course would be marked by lines of vertical cliffs, formed of the beds upheaved on the upcast side, if it had not been that these have been swept away by denudation, and the surface pared down to a level.

And, indeed, it is on such a supposition alone that we can understand how rocks could have been bent as sharply as they have been without fracture. That they were consolidated in many cases when they were bent is certain. Thus Sir H. De la Beche points out that in Pembrokeshire a thick mass of Limestone—the Carboniferous Limestone—and a great deposit of overlying Shales and Sandstones—the Coal Measures—share in the same contortion, which therefore could not have taken place till after the deposition of the latter. But during the time and under the circumstances necessary for the accumulation of the upper group, the Limestone, if it ever was soft, must have become perfectly consolidated.

Of the contortions shown in Fig. 58, Mr. Miall remarks, "The angles are sharp, but unbroken. You may easily test this by passing a finger over one of the bends. There is neither crack nor vein." And he disposes of the explanation that the rock was in an unconsolidated state when it was bent, by pointing out that some shells and corals preserved in it, which were certainly not originally plastic, are distorted by the folding.

With the view of throwing light on the origin of contortion, Mr. Miall carried on a series of ingenious experiments. He succeeded by means of pressure applied gradually for some length of time in bending thin plates of Limestone, but the bent slabs always cracked soon after the pressure was removed: this difficulty was partly overcome by embedding the pieces operated on in pitch. He very justly remarks that the frequent destruction by spontaneous fracture of bent plates, when removed from the machine, seems to imply that an indefinitely protracted and uniformly contorting force is needed to produce unbroken curvature; that resistance on all sides diminishes the risk of fracture; and that the results attained serve to strengthen the opinion that unbroken anticlinals and synclinals are formed only under a considerable weight of superjacent strata.* These experiments certainly seem to show that, if solid rock is to be contorted without fracture, there must be something to hold it together while the bending is going on; and the necessary force of restraint would be supplied by the weight of a mass of overlying measures. In Sir James Hall's well-known illustration of contortion,† a number of layers of cloth were laid on a table and pressed together by boards at either end. In this way they were forced into folds closely resembling the sharp contortions of rocks. But it was necessary to load them above by another board carrying a heavy weight, and this represents the mass of overlying strata, which must have been present when rocks were undergoing folding.

We saw reason, when considering the phenomena of metamorphism, to believe that the process went on deep beneath the surface. Now Metamorphic rocks are almost always highly contorted. We have here, then, another reason for believing that the rocks were deeply buried when contortion was produced.

Folding went on Slowly.—If the conditions under which the rocks were contorted were at all similar to those by which Mr. Miall obtained his results, the bending must have gone on very slowly. Some experiments by Professor Thurston, of the Smithsonian Institute, also point to the same conclusion. He found that if iron, which had been forcibly bent close up to the breaking point, was kept bent by pressure for seventy-two hours, it showed no tendency to return to its original form, but acquired a "permanent set;" and, what is still more to our purpose, it then became capable of further bending.‡

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* Geological Magazine, vi. p. 505; Proceedings of the Geological and Polytechnic Soc. of the West Riding of Yorkshire, new series, Part I. (1872); Popular Science Review, Jan., 1872.

† Transactions Royal Soc. of Edinburgh, vii. 85; Lyell's Elements, 6th ed. p. 50.

‡ Journal of the Franklin Institute, Jan., 1874. I am indebted to Mr. R. Hunt for calling my attention to this paper.

We can realise from these experiments how by a repetition of small bendings rocks, apparently the most inflexible, could little by little be folded into the sharpest imaginable curves.

Analogy leads us to the opinion that faults were not produced at one jump, but by a succession of small displacements.

Contortions more frequent in Old than Recent Rocks.—When touching on the consolidation of rocks, it was noticed that as a general rule the older rocks were the more completely consolidated; and it was pointed out that this was the case simply because they were older, and for that reason had been oftener and for longer periods subjected to the action of the forces which produce solidification.

A similar statement holds good for contortion; it prevails most largely, as a general rule, among the older rocks, and exactly the same explanation applies as in the case of consolidation.

In the early days of Geology this fact was held to prove that contorting forces acted more energetically during far distant periods of the earth's history than at present. But it is clear that the facts do not warrant this inference, and that they can be explained just as well in the manner just stated.

In the same way, when we see an old man more broken than the generality of young men, we do not infer that the wear and tear of life has necessarily been greater than usual in his case, but only that he has been exposed to it longer.

It is not intended to assert that there never was a time when the forces tending to produce contortion were more vigorous than now. Indeed, if there be any truth in the generally received view of the earth's early history, this must have been formerly the case. But it is not the greater solidity and excess of contortion in the older rocks that lead us to such a conclusion, but reasons that will be explained further on.

SECTION VI.—UNCONFORMITY AND OVERLAP.

What constitutes Unconformity.—A question of paramount importance in geological investigations may be conveniently treated of here. It sometimes happens that in a group of stratified rocks the beds come on, one over the other, each with the same dip as the bed next below it;

any contortions or faults affect all the beds alike, and the same general circumstances of lie and position pervade the group from top to bottom. Such an assemblage of beds forms what is known as a *Conformable Group*.

In other cases, in working our way across the rocks of a country, we find perfect conformity to prevail for a certain distance, and are then suddenly brought up by a decided break in the order of succession, and of such breaks we readily distinguish two kinds.

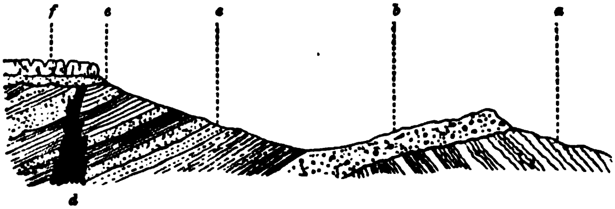

Fig. 96.—Section showing Unconformities accompanied by Change of Dip.

a. Silurian Schists.
b. Puddingstone, containing pebbles of *a*. } Carboniferous.
c. Shales and Sandstones, with thin beds of Anthracite. } Carboniferous.
e. Sandstone } Jurassic.
f. Magnesian Limestone } Jurassic.
d. Igneous dyke.

In the first case there is a sudden change in the dip and strike, or in one of them. An instance of this kind is shown in Fig. 96.* On the right we have steeply inclined beds of Schist dipping towards the right; on the edges of these there rests a group of Shales and Sandstones less steeply inclined and sloping in the opposite direction;

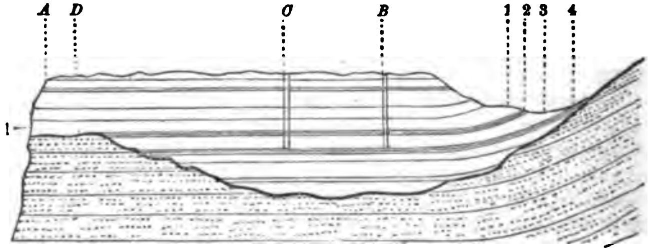

Fig. 97.—Section showing Unconformity unaccompanied by Change of Dip.

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* Taken from General de la Marmora's Voyage en Sardaigne.

these latter are capped by beds of Sandstone and Limestone lying perfectly flat. The different members of each of these three groups are perfectly conformable to one another, but in passing from each group to the one next above it we encounter an abrupt change of dip.

In the other kind of break all the beds have the same dip, but they can be separated into two groups, the upper of which rests on a worn and uneven surface of the lower or abuts suddenly, *without a fault*, against a slope or cliff formed of the latter. A case of this kind is shown in the diagram in Fig. 97, where the upper finely-bedded rocks lie in a trough, which has been worn out of the lower dotted group.

Meaning of Unconformity.—The occurrence of a break of either of these kinds is called an *Unconformity*, and the groups of strata separated by unconformities are said to be *unconformable to one another*.

Such are the observed facts, and our next business is to ask what they mean, and what are the events by which they were brought about.

Turning to Fig. 96, we know that the Schists (*a*) at one time lay flat at the bottom of the sea in which they were deposited. They have been tilted from their horizontal position, and, as they rose, denudation pared off the edges of the strata and produced the surface on which the bed (*b*) rests.

And all this must have been done before the deposition of the next group of rocks began. The tilting and denudation took time to effect; in many cases a very long time would be required for the removal of the amount of rock which we can prove must have been carried away.

The unconformity, then, we are now looking at is a proof *that an interval occurred between the deposition of the two rock-groups which it separates, and that during that interval no deposition of rock went on at the spot where the unconformity occurs; or that if any rocks were formed there during that interval, they have been entirely carried away by denudation.*

We shall see by-and-by that the different rock-groups of the earth's crust are in reality so many volumes in which is written an account of some of the events that went on during their formation; and, pursuing the metaphor, we may say that, where an unconformity occurs, there are certain of these volumes missing, and that there is consequently a blank space in the chronicle. But just as an historian, when his investigations are checked by coming across an imperfect copy of a work, is sometimes enabled to make good the defect by going to another library and recovering there the missing pages or volumes; so the geologist, when he finds at one spot an unconformity and a corresponding break in the chain of events he is endeavouring to trace out, may sometimes pick up some of the lost links in other quarters, where the deposition of strata has gone on with less interruption. This is the case in the Sardinian instance. The bottom rocks are known, by tests which will be described further on, to have been formed at the same time as certain of the slaty rocks of North Wales, and the overlying group is of the same age as the beds from which we in England draw our supplies of Coal. Now with us between these two groups of rocks there intervenes a great mass of strata known collectively as the Old Red Sandstone, the formation of which went on during the interval which is represented only by an unconformity in the Sardinian series. The section of the latter shows us that the deposition of two groups was separated by an interval, it tells us thus much and no more; from a study of English Geology we learn what was going on elsewhere during that interval, and infer that it was of considerable duration, because it allowed time enough for the accumulation of a vast thickness of strata.

Exactly the same remarks apply to the unconformity between the middle and upper groups of the section before us; and here again the rocks wanting in Sardinia are to be found in England and other parts of Europe.

In the second kind of unconformity the lower group has not been tilted before the deposition of the beds above. Any displacement from a horizontal position that has taken place affects both groups alike, and must therefore have been produced after the deposition of the upper; but *the lower beds have been denuded before the deposition of the upper beds began*, and, as time would be necessary for this operation, we have here, quite as much as in the first kind, a proof that an interval, unrepresented at the spot where the unconformity occurs, intervened between the formation of the two groups which it separates.

That the denudation described must have taken place will be evident by a glance at Fig. 97. The beds of the lower group could not possibly have been deposited so as to end abruptly on the slopes of the hollow which now exists in them. Each must originally have stretched across to the point where we find the corresponding bed on the other side, and the present interruption in their continuity must be due to the removal of portions of them.

Unconformities of this class vary very much in importance. Sometimes the erosion is such as might be brought about by a very trifling change in physical conditions, and so small in amount that no great time would be required to effect it. Such cases may be better described as "contemporaneous erosion and filling up,"* because they do not indicate the important break associated with the idea of unconformity.

In other cases the denudation has been extensive, and the interval required for it of long duration, and these may be fairly spoken of as unconformities.

An unconformity, then, of either kind shows us that, at the spot where it occurs, the process of rock formation did not go on continuously; that, at a certain point of time, a stop was put to deposition by the upheaval and conversion into dry land of the sea bottom; that by this means the rocks, which had been just laid down, were brought within the range of denudation, and portions of them worn away; that the surface thus formed was afterwards lowered beneath water, and a new set of rocks deposited on the truncated edges of the lower group.

On the other hand, steady, uniform deposition would give rise to a conformable group of strata; but the converse proposition, that conformity indicates the absence of any interval between the deposition of successive members of the series, is not necessarily true; for we can readily imagine that, after the deposition of any one bed, the supply of sediment might cease, and a long time might elapse before it was renewed and the bed next above laid down, and thus there would be an interval between the formation of this bed and the one next above it; but if the lower bed remained undisturbed during this interval, the two would be perfectly conformable to one another. In fact, the mere existence of a plane of division between two beds is proof of an interval between their formation, and this interval may have been a long one, unless there is independent evidence to the contrary.

In a word, an unconformity will bear but one interpretation—that the process of rock formation was suspended for a time, and that during that time denudation took its place.

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* An expression used by Prof. Jukes. A case of this sort is shown in Fig. 14.

We cannot be quite so sure of the meaning of conformity, because there are two ways in which it may have been produced. It may have, and in many cases has, arisen from a long, steady continuance of the same conditions; but in itself it affords no certain proof that such was the case, because the formation of two consecutive beds of a conformable group of strata may have been separated by an interval without any indication of the fact having come down to us.* To put the matter as shortly as possible, unconformity implies an interval, conformity does not exclude it.

Deposition on Sinking Sea-bottoms.—Again, conformity is not necessarily evidence that the sea-bed was absolutely at rest during the formation of the beds through which it prevails. We have many cases where strata, *all of which must have been laid down in shallow water*, are piled one over the other in perfect conformity to a thickness of thousands of feet. The only way we can account for this is by supposing that, during the whole of the deposition of such a group, the sea-bottom was slowly sinking, and that *the space through which it went down in any given time was just equal to the thickness of sediment accumulated during the same time.* By an adjustment of this sort the water would always be kept shallow, for, as fast as subsidence deepened it, deposition would fill it up again; and, if the movement affected the whole area over which deposition was going on, no unconformity would be produced.

General Conclusions.—We arrive, then, at the following canons. Conformity is produced when, during the deposition of a group of strata, there has been an absence of upheaval, depression, or denudation; or when, if either of these operations has gone on, it has affected the whole area over which deposition took place. Unconformity exists when upheaval and denudation have removed a portion of one set of beds and another set of beds have been afterwards deposited on the surface so formed. Or, more shortly, a continuance of the same physical conditions gives rise to conformity; unconformity has been produced by change in these conditions.

A simple illustration will, perhaps, bring home more clearly to the reader's mind the facts of unconformity and their interpretation. Suppose that, during a long, peaceful period, the various events in a nation's history were noted down as they occurred, and the volumes piled one above another on the floor of a library. The heap so formed may fairly represent strata conformably deposited during a long continuance of the same conditions. Suppose that a time of war and tumult followed, during which some of the volumes got disarranged, a part of the archives was destroyed, and throughout which the disturbed state of affairs prevented the carrying on of the work of the chronicler. This would cause a blank period in the history exactly corresponding to the gap indicated by a geological unconformity, and accompanied, like it, by disturbance and partial destruction of the record of what had gone before. On the return of more peaceful times, the annalist might resume his labours, and if the volumes he produced were laid upon the disordered remains of the earlier records, they would correspond very closely to the upper group of strata which an unconformity shows resting on the edges of the lower beds.

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* The existence and meaning of unconformity were recognised first by the master mind of Hutton. See Theory of the Earth, i. 432, 458; Playfair's Works, i. 216, iv 78.

Illustration of Unconformity.—In Figs. 98 and 99 an attempt has been made to show the results of a strong unconformity. The first is a perspective view of a model, on the upper surface of which the outcrops of various strata are shown by different patterns, while along the sides we see, as we should see in a cliff, a section showing the course of the beds underground. The second is a geological section along the line marked on the model. We see at a glance that there are two rock-groups, between the lie of which the most marked discordance exists. The lower, distinguished by a lighter tint, has been bent into a number of troughs and arches, which have been truncated by denudation, and a floor, marked by a stroke and dot line on the section, has been formed, on which the upper group rests in a nearly horizontal position. The latter has also suffered by denudation, and only two detached outliers remain of the sheet of it which once spread over the whole area: the connection which originally existed between the beds of these outliers is shown in the section by dotted lines. Further proofs of denudation previous to the deposition of the higher beds are furnished by a fault and dyke, which traverse the lower group but do not penetrate into the upper. Another fault, which affects both groups, and is therefore of later date than the formation of the upper, is seen on the left hand.

The clean cut section shown by the cliff puts beyond

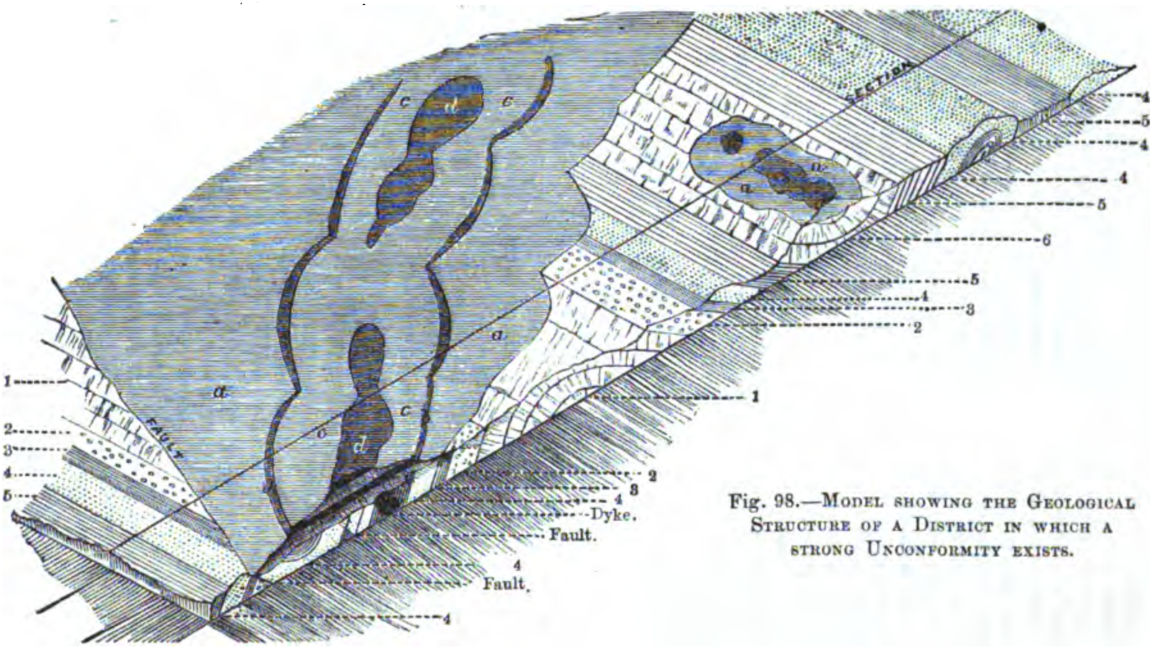

Fig. 98.—Model showing the Geological Structure of a District in which a strong Unconformity exists.

question the existence of the unconformity; but we will now go on to show how the unconformity might be detected by simply mapping the country geologically, even if the cliff section did not exist, and without paying regard to the difference in the dip of the beds.

If we trace across the country the run of the beds of either group, we find them always coming on, one over the other, in the same order. Among the lower set, (1) is overlaid by (2), and this is always followed by (3), above which the other members succeed in the order of the numbers which they bear in the diagrams; and this is seen to be the case in whatever direction we traverse the district, and whatever disturbance the beds have undergone. Similarly with the upper group; it matters not where we

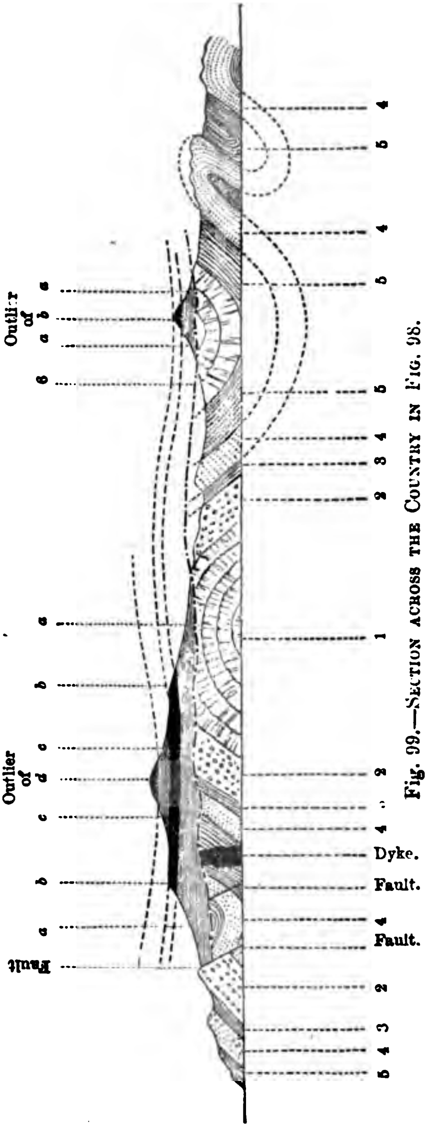

Fig. 99.—Section across the Country in Fig. 98.

descend the flanks of the hills which they compose, we always find them cropping out in the same order, *d* at the top, then *c*, then *b*, and *a* at the bottom.

But we meet with a very different state of things when we follow the line which parts the two groups. The bed *a* rests first on (2), it then stretches over (1), after leaving the latter it comes again to lie upon (2), and then creeps gradually on to higher and higher beds till it is in contact with the highest member (6) of the lower group; still further to the right it comes to lie upon (5) and (4) in succession.

Now this gradual passage of the upper group over the edges of the different members of the lower group can be caused only in two ways—either by a fault bringing one against the other, or by an unconformity between the two. On the left hand there is a fault bringing about this result; on the right the wavy and indented nature of the boundary would be all but conclusive against it being faulted, even if the cliff section did not show the absence of any fault.

Having assured ourselves, then, that there is no fault to cause the upper group to abut at different spots against different members of the lower, *we may accept this behaviour as conclusive proof in itself of an unconformity between the two groups.*

Incidental Proofs of Unconformity.—In some cases where such direct proofs of unconformity as we have just described are not forthcoming, we may detect its presence by evidence of a circumstantial kind.

It frequently happens that the bottom beds of the upper of two unconformable groups are Conglomerates, the pebbles of which have been derived from the lower group. This shows denudation, and therefore upheaval of the lower group before the upper began to be formed. This has been the case in the section in Fig. 96, with the bottom bed, *b*, of the middle group.

We may occasionally detect faults or igneous dykes which penetrate the lower group, but do not run on into the upper. Fig. 96 furnishes us with an instance of this; the dyke *d* terminates at the base of the bed *e*, and the abrupt way in which it is cut off shows that it must originally have extended higher up than now, and that it has been truncated by the denudation that produced the floor on which *e* rests. Similar cases are seen in the diagram Fig. 99.

When we find the lower of two groups of strata intensely metamorphosed and the upper unchanged, there is a fair presumption that the operation took place before the deposition of the latter, and that, therefore, an interval elapsed between the formation of the two.

Deceptive Appearance of Unconformity owing to Underground Dissolution of Rock.—In cases like these now under consideration, where the lower group is calcareous and the upper allows of the passage of water, the observer must be on his guard against too hastily inferring that an uneven junction necessarily means denudation of the former before the deposition of the latter. Under such circumstances it may be that the two may have been originally laid down in perfect conformity, and that subsequently carbonated water percolated down to the Limestone, dissolved it away, and gave rise to inequalities and pot-holes on its surface, into which the upper beds have settled down. In such a case the irregularity in the junction of the two groups, having been produced after the deposition of the upper, is no proof of an interval having existed between the formation of the two.*

Deceptive Conformity.—In the examples we have given the evidence for an unconformity is so clear that there is no room for a mistake; but unconformities are not always so easily detected, and in some cases an apparent conformity exists locally between two rock systems which are really violently unconformable to one another. As an instance we may take the Magnesian Limestone and the Coal Measures of Yorkshire, the relative lie of which is shown in the sketch-map and section in Fig. 100.

A geologist who confined his observations to the neighbourhood of the point *A*, would scarcely be able to detect there any signs of an unconformity between these two groups of rocks. The dip of both is in a general way to the east, and is so small that it would be quite impossible to say from such measurements as could be made in quarries or limited exposures of rock, whether there was any difference in the amount of inclination of the two formations. When we come, however, to map the country in detail, we find that the outcrops of the Coals, Sandstones, and other members of the Coal Measures over a great part of the field trend pretty steadily north and south, but that at either end they bend round to the east. In fact the portion of the Coal Measures exposed at the surface forms a half-basin. Now, over the central part of this basin the beds strike north and south, or in the same direction as the

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* See Quart. Journ. Geol. Soc. cf London, xxii. 402.

Limestone, and, as long as this arrangement prevails, the two formations exhibit no unconformity; but at either end of the basin, where the easterly strike sets in, we find the Limestone, as we go either to the north or the south, resting

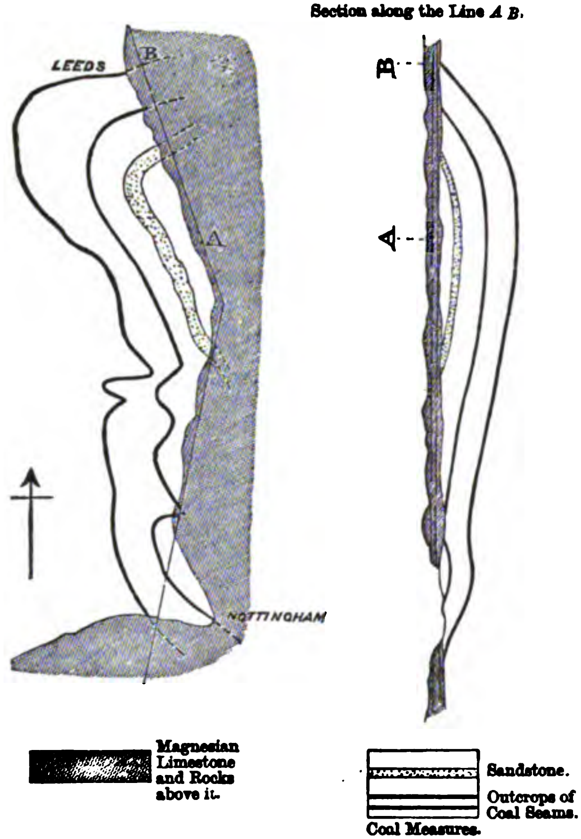
Section along the Line *A B*.
LEEDS
B
A
NOTTINGHAM
B
A
Magnesian Limestone and Rocks above it.
Sandstone.
Outcrops of Coal Seams.
Coal Measures.

Fig. 100.—Sketch-map of the Yorkshire and Derbyshire Coal Field.

in succession on lower and lower beds of the Coal Measures, and become aware how discordant the two formations are. We then realise that the Coal Measures have been thrown into a trough and largely denuded before the Limestone began to be formed. To give an idea of the amount of denudation, the Limestone at *A* rests on beds some three thousand feet higher up in the series than at *B;* so that at the latter point at least this thickness has been swept away.

Unconformities like these might escape the notice of a casual and hasty observer, but they would be certain to be revealed by the mapping of a large tract of country.

A case of deceptive conformity is shown in Fig. 97. The section at the point *A* gives no indication of unconformity between the two groups shown in that diagram, but the section taken as a whole shows that a marked unconformity exists.

The warning conveyed by such instances is, not to rely too much on apparent conformity, but to bear in mind that it may be only local, and to ascertain by widespread observations whether this is so or not, before concluding that a set of rocks form a conformable series. A single observation will often establish beyond doubt the existence of unconformity; extensive research will be required before we can safely say beds are conformable to one another.

Overlap.—When the surface of a group of rocks has been worn by denudation into hollows and these have been filled by the deposition of a second set of strata, it necessarily happens that each bed of the latter will extend over a larger area than the bed next below, and will cover it up and hide it from view; so that if we made a section across a country where this had occurred, we should find each bed of the upper group reaching across the bed immediately beneath to abut against the sloping sides of the hollow. This is called an Overlap, and each bed is said to overlap the bed below it.

In diagram, Fig. 97, we see very clearly, on the left-hand side, the bed (1) overlapping (2); this again overlaps (3), and the latter overlaps (4), and so on. The existence of the beds below (1) would not have been known, if it had not been that on the right-hand side denudation has removed a portion of the rocks that once covered them, and has laid them open to view. Similarly, in section 4, Fig. 102, (3) overlaps (2), and is itself overlapped by (4).

Occasionally we find some among the different members of a formation occurring only in patches here and there, because the conditions necessary for their formation existed only at certain spots; at the same time these different members overlap one another against the sloping surface of a group of older rocks. Great complication is thus introduced, which it requires the utmost care to unravel. A good instance occurs on the north-eastern edge of the Lake district. If we turn to a geological map of England, we see that the old rocks of the Hill country, which are distinguished as Silurian, are flanked by a belt of a newer formation, the Mountain Limestone; but every here and there between the two there come in detached patches of an intermediate group, called the Old Red Sandstone, which consist of Conglomerates and Sandstones. The fact that the latter does not form a continuous band between the Silurian rocks and the Limestone, but occurs only in isolated areas, is due partly to the circumstance that it was deposited only at certain spots, and is therefore not present at all in some places, and partly to its being overlapped by the Limestone, and so concealed from view at some places where it does exist. During the deposition of these rocks the order of events was as follows. The boss of hill country was upheaved and carved out by denudation into something like its present shape very long ago; it was afterwards slowly lowered beneath water, and, as it went down, banks of shingle were piled up along the successive shore-lines formed by its gradual submergence. It is easy to see that these would reach their largest dimensions off the mouths of rivers, where the materials for their formation were supplied in greatest abundance. It is also not unlikely that the hills were then occupied by glaciers, and, when one of these came down to the water, the load of rubbish on its back would yield plentifully matter suitable for the formation of shingly deposits. And thus it came about that the Conglomerate never formed an unbroken fringe all round the hills, but was deposited only in patches at certain spots. As depression went on, it was accompanied by a change in physical conditions; the ice disappeared, and the volume of the rivers decreased, so that they brought down fine Sand instead of their former coarse detritus; thus there was next formed a group of Sandstones, less coarsely grained than the Shingle beds which preceded them, and these covered up the latter, and extended some way higher up the Silurian slope. Lastly, continued depression gave rise to a deep and extensive sea, in which Limestone was formed; this was mainly of organic origin, but it contains in the neighbourhood of the Lake hills beds of mechanically formed sediment derived from the adjoining land. This last formation covered up the two preceding groups, and abutted at a

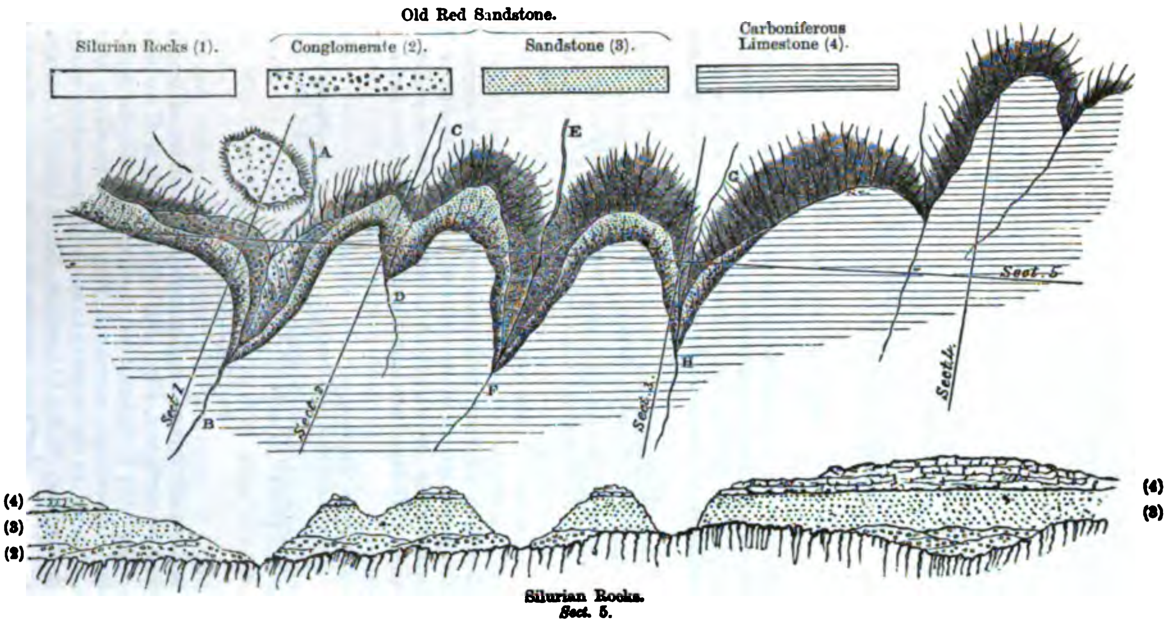

Fig. 101.—Sketch-map showing the Manner of Occurrence of the Old Red Sandstone on the Margin of the Lake District.

higher level than they against the Silurian rocks. A section which crossed country where all these groups are present would run as in section 4, Fig. 102.

But the reader may ask how we become aware of the existence of the Sandstone and Conglomerate, which in the section just given are hidden from view by the Limestone. Their presence is revealed to us by the occasional removal of the overlying beds by denudation, in the way shown by the sketch-map in Fig. 101. The district is traversed by river valleys: of these *A B* and *E F* run over ground beneath which all four rock groups are present, and cut down deep enough to show them all; section 1, Fig. 102 shows what may be observed in either of these valleys. The valley *C D* lays bare the Sandstone, but does not cut down to the underlying Conglomerate, the position of which is marked in section 2, Fig. 102. The valley *G H* crosses a spot where the Conglomerate is absent, but shows Sandstone and Limestone; section 3, Fig. 102 runs along this valley. Lastly, in the country to the right no valleys reach beneath the base of the Limestone, but it is likely enough that both the underlying groups may be locally present

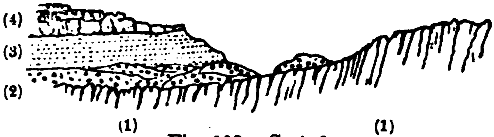

Fig. 102.—Sect. 1.

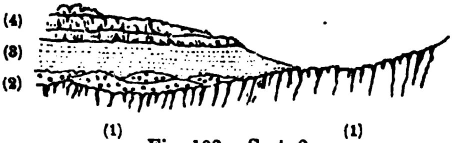

Fig. 102.—Sect. 2.

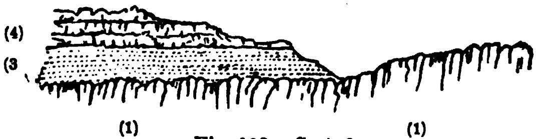

Fig. 102.—Sect. 3.

beneath, as shown in section 4, Fig. 102. The section No. 5, placed beneath the map, will further illustrate the irregular occurrence of the Conglomerate.

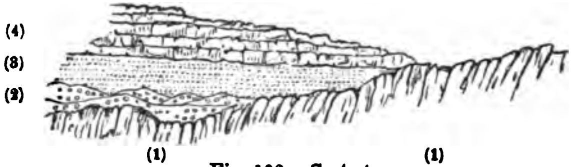

Fig. 102.—Sect. 4.

It is right to add that the Sandstone, like the Conglomerate, is local in its occurrence; it is represented as continuous in the figures to avoid confusion.

Practical Bearings.—It is of the utmost importance to understand the bearing of unconformity and overlap when we endeavour to determine the underground continuation of strata from observations made at the surface. Thus in the diagram, Fig. 97, suppose the beds (2) and (4) to be Coal seams, which are being worked from their outcrops on the right towards the left. At the basset edges and in the sinkings at *B* and *C* they are regularly overlaid by the bed (1) and separated by the bed (3), and we might be apt hastily to infer that wherever we found the bed (1) we should also find these seams at the usual distance beneath it. But if, on the strength of the presence of (1) in the section at *A*, we commenced to sink at *D*, our enterprise would be a failure, because the Coals we were in search of have abutted unconformably against the slope of an underground ridge of lower rocks before reaching that spot. But a careful examination of the whole of the section at *A* would evidently have prepared us for the possibility of this being the case, for it would have shown us immediately beneath (1) not the Coal seam (2), but a totally different rock, and opened our eyes to the true structure of the district.

A most serious failure arising from a cause of this kind occurred in a boring for water at Kentish Town, for the details of which see *Quarterly Journal of the Geological Society of London*, xii. 6, and the Memoir of the Geological Survey of England, on Sheet 7, Appendix 3.

As another instance I may mention an abortive boring for Coal in South Staffordshire, described in the "Manchester Science Lectures for 1871," 2nd series, p. 17.

Throughout this chapter we have constantly assumed the removal of enormous thicknesses of rock by denudation. Many of the sections we have given are in themselves proofs that such an assumption is fully justified by facts, but the reader will realise more fully the constant repetition of denuding action, and the vast extent to which denudation has gone on, after going through the next chapter.

CHAPTER X.

HOW THE PRESENT SURFACE OF THE GROUND HAS BEEN PRODUCED.

"Now concerning the exaltation of the mountains above the vallies it appeareth to come to pass by the water in former times, whose property is to wear away by its motion the most loose earth, and to leave the more firm ground and rocky places highest."—A DISCOVERY OF SUBTERRANEAL TREASURES (GABRIEL PLATTER, 1738).

"That mighty trench of living stone,
Where Tees, full many a fathom low,
Wears with his rage no common foe;
Condemned to mine a channelled way
Through solid sheets of marble grey."
SCOTT.

SECTION I.—PROOFS THAT THE SHAPE OF THE SURFACE IS DUE TO DENUDATION.

WE have now made ourselves acquainted with the processes by which the materials that compose the ground on which we live and move were brought together, compacted into their present form, and placed in their present position; our next step will be to inquire how the surface of that ground has had its present shape given to it—how mountain-chains, table-lands, hills, valleys, and plains, and all the lesser inequalities that diversify the face of the earth, were produced.

Surface due to Denudation.—We saw in the last chapter that the crust of the earth has been from time to time crumpled and folded into troughs and arches, and nothing would be more natural, when we see a mountain or hill, than to suppose that it is one of the arches, and that the valley which lies at its foot runs along the line of one of the troughs; that, in fact, if we were to cut a deep trench across hill and valley, we should see in its sides that the rocks were arranged underground, as in Fig. 103.

Nothing, certainly, could be more natural than to suppose this would be the case; but a very little examination suffices to show us that no supposition could by any possibility have been made so utterly contrary to fact. In a very large majority of cases we find that the rocks that form a hill, lie in a trough, instead of being bent up into an arch; and that a line of valley, instead of coinciding with a trough, runs along the crest of an arch on the rocks below.

In other cases the hills and valleys have apparently not even so much connection as this with the folds into which the rocks have been bent. And even in those cases where the rocks forming a mountain are arched and plunge down on each side in the same direction as the slope of the ground, if we draw a section across the hill, and are careful to put in the inclinations of its sides, and of the beds composing it, as they occur in nature, we see at once that the arch is incomplete, that large portions of it have been carried away, and that, though the formation of the hill may have begun with a bending up of the rocks, some other cause must have operated on it to give it its present outline.

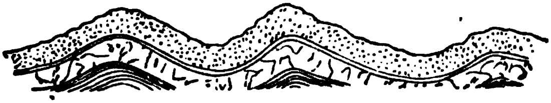

Fig. 103.—Section showing what would be the Geological Structure of a Country if the Hills coincided with Anticlinals.

The section in Fig. 104 would give a truer idea of the relations between the shape of the ground and the lie of the rocks beneath it. On the left we have two hills, the rocks of which lie in troughs, and valleys between cut out of the crests of arches in the rocks; then follows a tract where the beds are folded into sharp curves, but the surface, instead of following these curves, has been planed away till it cuts across them in every direction. On the right are lofty mountains, from the summit of which the beds dip away on each side in the same general direction as the slope of the ground, and where surface outline does follow, to a certain extent, the flexures of the rocks, and a broad valley between in which the arrangement of the rocks is trough-like. But look at this last case a little more closely; the surface is nowhere formed for any space by a plane of bedding, the arch is more or less truncated and defaced, and, in order to see it as it was when the rocks were first folded, we should have to put back the portions shown by dotted lines, which have evidently been carried away. It is easy to see, for instance, that portions only of the bed marked *A* remain on the mountain-tops and in the valley; if it had originally the same thickness throughout, it must once have reached up to the dotted continuation of its upper surface, and the parts between that line and the present surface are gone. The group of beds marked *B* also so exactly correspond on opposite sides of the chain, that we feel sure the portions now so widely disconnected must have once formed parts of an unbroken sheet of strata, that this has been bent in the direction shown up in the air by the dotted lines, and the portion between the two present outcrops has been removed. The reader will see by-and-by that it does not necessarily follow from this that the mountains have ever been as high as the restoration of the missing parts of the beds would make them; all that is asserted is, that the portions between the dotted lines and the surface have been removed.

The inequalities of the surface of the ground, then, are not due, or are due only in a minor degree,

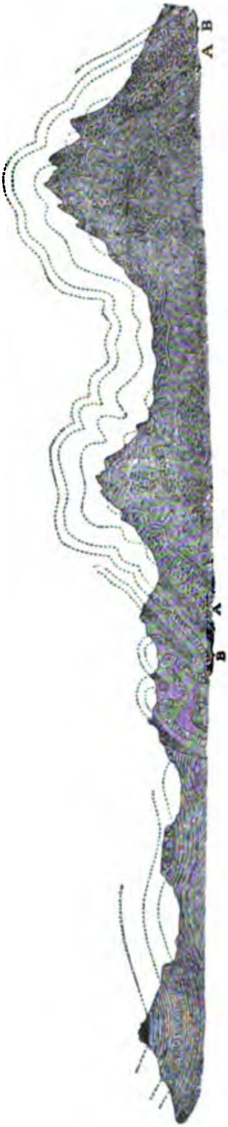

Fig. 104.—Section showing the true Character of the Relations of the Shape of the Surface to the Underground Lie of the Rocks.

to the folds into which the rocks beneath it have been thrown; some words used a little way back point unmistakably to the cause to which they are mainly due. Completing the curves in Fig. 104, and restoring the arch to its original shape, we find that parts of it have been *carried away*. Again, why does the hill on the left stand up so conspicuously? The rock at the summit and those on its flanks did not originally terminate where they do now, but stretched right and left, as shown by the dotted lines. These dotted parts have been *carried away*. The reader has doubtless before this said to himself, "Yes; and what carried them away can have been nothing else but denudation;" and he will be right, for, as far as we know, there is nothing else that can have done it.

The conclusion, then, we come to is, that in most cases valleys have been carved out by denudation, and hills are what denudation has spared; and that even in those cases where hills and valleys may have *originated* in a bending up or bending down of the rocks beneath them, their outline is still very largely due to denudation.

It will be enough to refer the reader to two of the countless instances in which not a doubt can exist that striking hills are merely remnants that have escaped denudation. No better proofs of the truth of this assertion can be found than the mountains on the west coast of Sutherland and Ross, figured in "Siluria," p. 170, and so eloquently described by Hugh Miller ("The Old Red Sandstone," p. 56); and the Scùr of Eigg, described by Professor A. Geikie (Quart. Journ. Geol. Soc. of London, xxvii. 303.)

The truth that the present inequalities of the surface are mainly due to denudation was first clearly seized upon by Hutton. His conclusions are thus elegantly summed up by Playfair. "It is where rivers issue through narrow defiles among mountains that the identity of the strata on both sides is most easily recognised, and remarked at the same time with the greatest wonder. On observing the Potomac, where it penetrates the ridge of the Alleghany Mountains, or the Irtish, as it issues from the defiles of Altai, there is no man, however little addicted to geological speculations, who does not immediately acknowledge that the mountain was once continued quite across the space in which the river now flows; and, if he ventures to reason concerning the cause of so wonderful a change, he ascribes it to some great convulsion of nature, which has torn the mountain asunder and opened a passage for the waters.

It is only the philosopher, who has deeply meditated on the effects which action long continued is able to produce, and on the simplicity of the means which Nature employs in all her operations, who sees in this nothing but the gradual working of a stream, which once flowed over the top of the ridge which it now so deeply intersects, and has cut its course through the rock in the same way, and almost with the same instrument, by which the lapidary divides a block of marble or granite." *

Amount of Denudation.—It is desirable at the outset that we should clearly realise how enormous has been the amount of the matter carried away to form the present surface of the ground. For this end the reader cannot do better than turn to Professor Ramsay's paper, "On the Denudation of South Wales and the adjacent Counties of England" ("Memoirs of the Geological Survey of Great Britain," vol. i. p. 297). To illustrate the methods employed to calculate what is the quantity of rock that has been removed, one of the sections of that paper is reproduced, with trifling modifications, in Fig. 105. The part drawn with strong lines represents the rocks below the surface; it is constructed by first obtaining an accurate profile of the ground by levelling; the different beds that come out to-day along the line are then examined, and their dips measured, and they are then drawn in, each with its proper dip. In this way, starting on the south, we pass over four groups of rocks, which are called respectively Coal Measures, Carboniferous Limestone, Old Red Sandstone, and Silurian, and come out one from below another in the order in which they have been named, with a steady rise to the north. About *A* the southerly dip begins to decrease, a little farther to the north we reach a point where the beds are observed to lie flat, and after passing this point a dip to the north sets in and gradually increases in amount. This shows us that *A* lies on the crest of an arch, or anticlinal, into which the rocks have been bent. If we continue the same kind of observations, we find that this arch is succeeded by a trough, and the trough again by a second arch, on the northern flank of which the dip is steadily to the north up to the end of the section.

In the Silurian rocks there is a well-marked and easily recognised bed of Limestone marked by a black band. This bassets at *B* and *C*, but the bed cannot have originally ended at these points as it does now. Before the strata

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* Works i. 116.

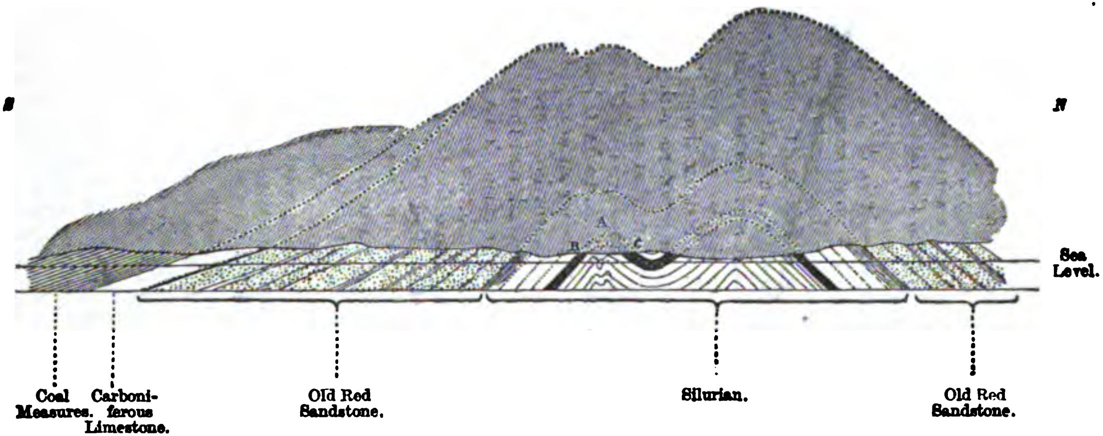

Fig 105.—Section to show the Amount of Rock that has been carried away by Denudation in order to form the present Surface.

were folded into their present form, it must have spread out as an unbroken sheet through the body of the Silurian rocks; and if we carry on its under and upper boundaries, bending them so that their dip may be always the same as that observed in the rocks beneath, we shall see how much of the Limestone, and of the beds under it, has been swept away in the course of the formation of the present surface. In the same way we determine the original connection of the bassets of this bed at *C* and *D*. Again, the Old Red Sandstone appears on both sides of the arch, but it cannot, any more than the Limestone bed, have ended originally as it does now. Let us carry on its upper and under boundaries, being careful to keep them everywhere parallel to the curves drawn for the Limestone bed, and we shall obtain the outline of the belt which once connected the detached outcrops on the southern and northern flanks of the arch.

The lines showing the former connection of the rocks, obtained in the manner just described, are dotted, and the tinted space between them and the surface shows how much has been swept off by denudation. The scale of the section is the same for heights and distances, so that everything is in its true proportion, and a glance will show how insignificant is the portion of the rocks that now remains, compared with that which has disappeared. The tinted portion in the figure is more than two square miles in area, so that, for every mile in the length of the anticlinal, upwards of two cubic miles of material must have been swept off to give us the present surface—enough to cover the whole of Great Britain to a depth of nearly a foot. And this is not all, for probably not only the Old Red Sandstone, but the Carboniferous Limestone and the Coal Measures as well, were once continuous over the area, and they are wholly gone along the greater part of the line.

SECTION II.—THE SHARE OF EACH DENUDING AGENT IN PRODUCING THE SHAPE OF THE SURFACE.

The surface of the earth, then, has been carved into its present shape, and denudation is the instrument that did the work. We have already seen that a number of different agents take part in the process of denudation, and we must now inquire how the task has been portioned out among them. In a former chapter on denudation we dealt mostly with the character of the waste resulting from its action;

we have here to look to the kind of surfaces that each of its cutting tools gives rise to.

Share of the Sea.—We will begin with the sea. A very little reflection will convince us that even at moderate depths the sea can do very little denuding work of any kind. We have seen that running water by itself is not able to cut or wear the rocks it flows over; but that, if the current is strong enough to carry in suspension, or roll along coarse sediment, a large amount of erosion is produced by the aid of the latter. Now the circulation of the depths of the ocean is carried on by currents in all probability of very moderate velocity; and the water, if it hold anything in suspension, must be charged with fine mud or ooze instead of the rough sediment which enables rivers to exert so powerful a cutting action. That this is the nature of a very large proportion of deep sea bottoms has been abundantly shown by soundings, and even in the cases where the sea-bed is strewn with coarser detritus, a large fragment is of rare occurrence. Professor Wyville Thomson gives two such cases met with in dredging to the north of Scotland. In one haul the largest pebble weighed 421 grains or ⅞ of an ounce, and may have been about the size of a walnut, and no other was met with anything like so large. In another case 718 fragments were brought up from a depth of 1,443 fathoms; one weighed 3 grains, the rest being from ⅛ to a ¼ of a grain in weight.*

The deep portions of the sea, therefore, do not possess the conditions necessary for denudation, and we may conclude that the only change that can happen to a surface buried beneath them will be the gradual filling up of any inequalities that may exist by the deposition of fine sediment.

But it is otherwise when we come to the coast-line. There we find abundant implements of destruction furnished by the piles of broken rock and rubbish, which atmospheric disintegration and the undermining of the waves are always detaching from the cliffs. These the breakers, as they are driven in by violent gales, hurl against the rocks of the shore, and in this way incessant destruction of the latter goes on, the land is slowly worn back, and the sea advances steadily inland.† But this takes place only between the limits of high and low tide, and practically marine denudation is confined to this zone.

* Depths of the Sea. App. C.

† For details the reader may turn to Prof. A. Geikie's Scenery and Geology of Scotland, chap. iii.; Lyell's Principles, 10th ed., chaps. xx. and xxi.

The sea then *acts powerfully in working back the coast-line, but it does not exert any appreciable wearing action below the level of the lowest tide;* the result, therefore, of marine denudation must be to *wear down a country submitted to its influence to an even surface coinciding approximately with the level of the lowest tides.* When it has done this, it can do no more in the way of destruction, and it suddenly changes its part to that of a conservative agent, for its waters protect the plain so formed from the action of other denuding forces.

Of course it is not intended to assert that the sea everywhere advances at the same rate; its progress depends on the hardness and structure of the rocks opposed to it, as we shall see more fully in a subsequent section of this chapter. It is this irregular advance that gives rise to bays and promontories and other inequalities of the coast-line; but, given time enough, even the boldest headland will be at last cut back. Isolated pinnacles, stacks, and skerries often hold their own for a long time against marine denudation, and stand up as landmarks to show the space over which it has worked its way, but in the end these are undermined, topple over, and are cleared away.

Plain of Marine Denudation.—The even surface that would result from the action of marine denudation alone is called a "Plain of marine denudation."

But in order to get such a plain we must not have any denuding forces at work besides the sea, for a very short exposure to subaërial denudation would soon destroy the uniform flatness which is its characteristic feature. Such a thing then as an unmodified plain of marine denudation never can have existed; and if there ever had been such a thing, we cannot expect to find any cases where it still retains perfectly its original character.

But by careful attention we can yet detect, even among the wonderfully diversified features of the present surface, traces of the horizontal planing of the sea by which that surface began to be formed. If we draw a section on a true scale across a country free from great mountain chains, it will in many cases be something such as is shown in Fig. 106. There will be hills and valleys, but it will be found possible to draw a straight line, *A B*, gently inclined seawards, that will touch, or nearly touch, the tops of most of the hills, while none of them will rise above it. If we took a raised map of the country and laid a flat board upon it, the same would be true for the board. Now it is likely that the surface represented by the board is the flat, that would have followed from marine denudation, if other denuding agents had not come in to modify the result which, acting alone, it would have produced.

A very striking instance where such a plain as we have described can still be very distinctly recognised, was brought before the writer's notice during a short journey on horseback over the wild country in the west of Andalusia. At first view, this region seemed to be a gently undulating expanse, stretching out as far as the eye could reach, over which it looked as if one could ride straight away without check or hindrance. A very short time sufficed to show how different the reality was from the appearance. Steep-sided valleys, sometimes deserving the name of ravines, stretched across the route in quick succession, down which the horses had warily to pick their way, and out of which they had laboriously to toil, and for a great part of the way the rate of progress did not practically exceed a foot's pace. The conviction was forcibly brought home to the mind that the history of the formation of the surface was something like this. The country had been first smoothed away by some horizontally planing force to an even surface, and afterwards the valleys had been cut down below its level by a trenching process that acted vertically. After what has been said the reader will recognise the sea as the first of these agents, and he will shortly see that the excavators of the valleys have been rivers that ran in them.

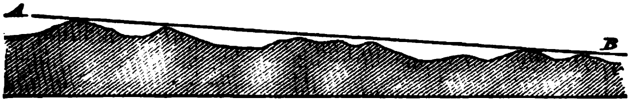

Fig. 106.—Section showing the probable Relation of the present Surface to an old Plain of Marine Denudation.

Share of Subaerial Denuding Agents.—Rivers.—We may next turn our attention to subaërial denuding agents, and first among these we will take rivers. The coarse sediment that is swept along the bottom wears away the bed, and therefore rivers, as long as they have sufficient fall, are constantly *deepening* their channels. The banks are also undermined, and from time to time portions, which have been thus deprived of support, break off and fall into the stream, and the channel thus becomes *widened.* But its sides, from the way in which they are formed, will always tend to be steep; their inclination will depend, just as in the case of a railway cutting, on the angle at which the material of the banks will stand; but it will always be considerable, unless some other denuding agent comes in to modify the results which would be produced by river action alone.

Rivers, therefore, are denuding tools, which tend to cut steep-sided trenches across a country; and these trenches they are continually deepening as long as they have any appreciable fall.

It will be at once objected to this generalization, that this is not the character of the river valleys we are most of us acquainted with; but the reasons for this is, that we have very few of us seen a valley that is due to river action alone. In the formation of most river valleys other denuding agents besides the stream that flows in them have had a share, and the shape of the valley is the result of the joint action of all. But a case will be given immediately in which the river has not been interfered with, and here we shall see that the result has been exactly such as we described.

We will first point out how most river valleys lose the trench-like form with which they must have started. Rain and the action of the weather round off the edges and break down the sides of the trench, and thus the steep-sided gorge gradually opens out into a broad valley, and the widening goes on as long as the slopes are steep enough to allow the disintegrated matters to be washed down into the stream. One test of the correctness of this explanation readily suggests itself. If it is true, the width of the valley ought to depend on the ease with which the rocks on its flanks yield to atmospheric wear. This is found to be the case. Many river valleys show along their course alternations of broad flats and narrow steep-sided gorges; in such cases it is always found that, where the valley is broad and open, the river is running across easily denuded strata; but that, wherever a ravine occurs, its banks are formed of unyielding rocks. An instance of this is shown in Fig. 107; the portion of the valley in the foreground slopes gently up from the river-banks, but when the river crosses the range of hills in the distance the valley contracts into a ravine. On the right-hand side is a section, such as would be given by a very deep railway cutting, which lays open the geological structure of the country; and this shows us that the part where the gorge occurs is formed of hard, thickly-bedded Limestone, while the more undulating portion is underlaid

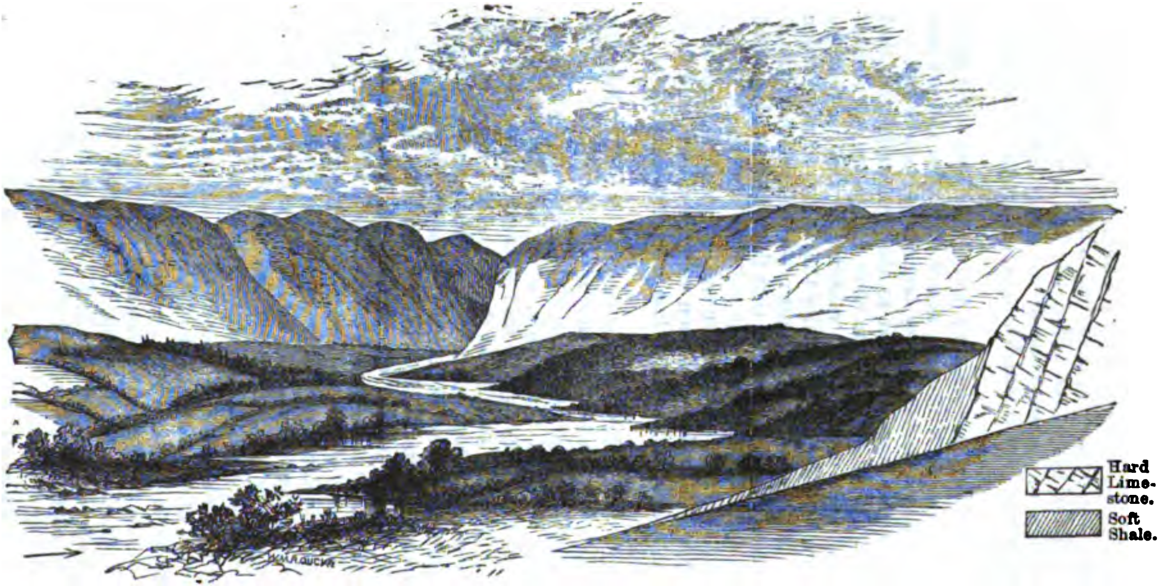
Hard Limestone.
Soft Shale.

Fig. 107.—View of a River Valley, broad and open where it runs across Soft Rock, and contracting into a Gorge where it cuts through Hard Rock.

N.B.—The river is running *from* the spectator.

by soft Shale. Examples of this kind are common enough round the border of the Carboniferous Limestone of Derbyshire; as, for instance, where the River Derwent enters the Limestone tract about a mile above Matlock. The gorge here was originally only just broad enough to admit the river; and, when the high road was carried along the valley, the gap had to be widened by blasting away its rocky wall. We also frequently meet with river valleys whose section is like that in Fig. 108, broad with gentle slopes in the upper part, and a deep steep-sided trench, in which the river flows, in the middle. In such a case we find on examination that the upper beds are soft, and have been largely worked back by atmospheric causes; but as soon as the river had cut down to the more indestructible rock at the bottom, the trench which it ate out retained more nearly its original shape.

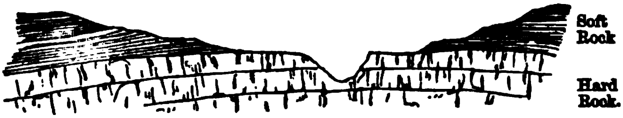

Fig. 108.—Section across a River Valley, with gentle Slopes where the Banks are formed of Soft Rock, narrow and steep-sided where the Stream has cut down to Hard Rock.

Canon of Colorado an Example of River Action.—But these are matters that will have to be considered more fully further on; let us now see if we can anywhere hear of a river valley, where the stream has been let alone to do its work without the interference of other denuding agents, and learn what the result of that work has been. No better instance can be given than the well-known one of the Colorado River of the West, which empties itself into the Gulf of California. This stream flows for nearly three hundred miles of its course in a profound chasm, sometimes not more than fifty yards wide, the walls of which are approximately vertical, and vary in height from three thousand to six thousand feet; that is to say, the gorge is in places more than a mile deep.

No one can deny the trench-like character of such a channel; but are we sure that it has been cut by the river? The first explanation to suggest itself is, that this mighty chasm is a rent torn open by an earthquake or some similar convulsion, which the river has appropriated to its use. A little examination shows that this has certainly not been the way in which it was formed. The beds on opposite sides correspond perfectly; and the rock at the bottom, though deeply eaten into, is nowhere fissured and broken. But what completely settles the question is the fact that the country on both sides is channelled in every direction by innumerable narrow, steep-sided, winding chasms, which differ from that of the river only in size. These minor chasms all spring from the main gorge, and divide and subdivide as they recede from it; and their arrangement is so exactly like the branching network of a river and its tributary brooks, that there cannot be a shadow of a doubt that it was from such a system that they took their rise, and that each has been made by a stream eating its way lower and lower down, till this extraordinary assemblage of ravines, which are known by their Spanish name of cañons, has been produced.

This explanation is further confirmed, when we find at various points along the cañon patches of River Gravel lodged far above the level of the highest floods, and great sheets of similar Gravel, spreading over the flat bottom of the valley where it opens out below the gorge, the pebbles of which are formed of the rocks at the top of the wall of the cañon.

There can be no doubt, then, that the Great Cañon, and the innumerable ravines that spread out from it, have been formed by streams that run, or once ran, in them; and, what is more, the other condition we were in search of is also satisfied here, *no other denuding force has had a share in their formation.* For the district is practically rainless; and this is the reason why the cañons are so markedly trench-like—there has been no atmospheric wear to round off their edges and work back their walls.

We have found, then, here exactly what we wanted, a case of river-action pure and simple; and learn from it that rivers are denuding tools that act vertically, and that the channels they cut, when they are left to themselves, are steep-sided trenches.

The line of reasoning we have been pursuing will be perhaps made somewhat clearer, if we consider a little more in detail the formation of the Great Cañon and its tributaries. The country traversed by it is an elevated plateau, varying in height from five thousand to eight thousand feet above the sea; from this table-land a wall of mountains rises on either side, the Sierra Nevada on the west, and the Rocky Mountains on the east. The two bounding ranges run together both on the north and south, and in this way the tract becomes hemmed in on all sides by lofty mountains, and a great basin is formed. The western barrier is breached by three great openings, through which the drainage is discharged by three great rivers, of which the Colorado is one. The district is all but rainless; and, as all the water that is brought into it by the rivers flows along the bottom of profound cañons, the surface is dry and parched, and in great part desert land. But this was not always the character of the region. The system of cañons shows that it was once traversed by a network of streams, which flowed on the surface, and there are other reasons for believing that it was formerly well watered and fertile. It is not unlikely that originally the basin was occupied by a lake, or lakes, the waters of which were dammed back by the western mountain barrier, and whose overflow escaped through shallow depressions at the same spots where that range is now cut through by the openings already mentioned. At that time most likely the country stood much lower than now; but after a while elevation set in, and, as the land rose, the notches in the mountain range, through which the water ran out, were worn deeper and deeper, and the level of the lakes lowered, till the basin was at last laid dry. Thus was formed a tract of land, the drainage of which passed out through the gorges which had in their infancy given exit to the water of the lakes. Elevation still went on, and in consequence the gorges, and the river channels that emptied through them, were continually being cut deeper and deeper, till their present enormous depth was attained. One thing more was wanted to give the country its present peculiar character; rain would inevitably wash in the sides of the chasms and convert them from cañons into broad valleys. This result was prevented by a decrease in the rainfall, which may have been brought about thus. Before the region reached its present height, though it was surrounded by a belt of hills, these were of too moderate an elevation to intercept the clouds that passed over them, and moist winds therefore were able to reach the interior; but when the encircling hills became converted into lofty mountains, the wind, from whatever quarter it blew, was robbed by them of all its moisture before it reached the central plateau, and the latter became in consequence a rainless area. The gradual elevation of the land, then, had a twofold result: the rivers were enabled to go on deepening their channels, and rain was kept away. The cañons owe their formation to the first of these results, and their preservation to the second.*

Other Subaerial Denuding Forces.—The whole army of subaërial denuding agents assist in the work of widening the trench-like excavations to which rivers give rise, and in destroying in countless ways the uniformity of the plain of marine denudation.

A description of the mode of action of each has been given in Chapter III., from which the reader will be able to gather how each contributes its share to the general result. The peculiar surface features due to moving sheets of ice will be treated of in a separate section.

Landslips.—Among the many ways in which subaërial denuding forces bring about the widening of valleys, one of the most important is by the formation of landslips.

When the top of a hill or the summit of a steep ridge is capped by hard, massive, heavy rock, beneath which lie softer and more yielding beds, the weight of the rock atop tends to crush down and drive outwards along the hill-face the soft strata below. In this way portions of the capping are deprived of support, break off, and slide † or topple over down the slope. Very frequently this goes on till the whole hillside from top to bottom is strewn with slipped masses piled one on the top of another in wild confusion. In every case where the above conditions are present, there will be a tendency to the formation of landslips, and sundry other circumstances will increase this tendency and render their formation the more easy. Firstly, the breaking off of the upper rock will take place the more readily, if it be traversed by large open joints. Again, if the dip of the beds be from the hillside into the valley, that is towards the side on which there is no support, the surfaces of the beds form inclined planes, down which detached portions of rock tend to slide; on the other hand, if the dip be into the hill, there will be no tendency to slide, and landslips can be formed only by the crushing out of soft underlying strata. Further, if the cap be an open porous rock, and the beds below impervious, we have one of the most important aids in the formation of landslips. The water which sinks into the upper bed descends till it reaches the impervious stratum below; being there unable to penetrate lower, it runs off along the plane of junction, and the moistening of the upper surface of the bottom stratum either makes the inclined floor, on which the mass above rests, slippery, or in some other way renders motion easier than it would be if the surface were dry.

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* For details about this extraordinary region, see the Report of the Exploring Expedition of the American Government (Washington, 1861). There is a good abstract in Nature, i. 434, and a description of the plateau in Sir Wentworth Dilke's Greater Britain. See also Prof. Hayden's Sun Pictures of the Rocky Mountains, chap. vii.

† It is perhaps hardly correct to use this word, for there would be too much friction to allow of pure sliding. By what means exactly the loosened portions are enabled to move is not very certain, but move they do.

The section on Fig. 109 illustrates an actual case where all the conditions tending to the formation of landslips are found together. The left bank of the valley is crowned by a thick bed of Sandstone, which is massive and heavy, traversed by large open joints, and pervious to water; beneath it are beds of Shale nearly impervious, and so much softer than the Sandstone that water can easily reduce them to a state of mud; the dip also is down into the valley. This combination has produced the result that might be expected, and the whole flank is covered with large landslips. On the opposite side, any tendency there may be to the formation of landslips is counteracted by the dip of the beds into the hill, and not a single slip has occurred.

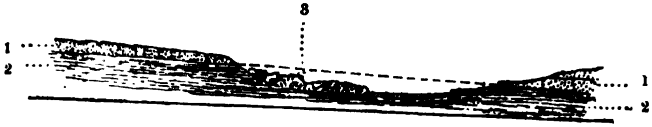

Fig. 109.—Section to illustrate the Formation of Landslips.

1. Massive, jointed, pervious Sandstone.
2. Soft, impervious Shale.
3. Landslips.

One or two additional cases of well-known landslips may be noticed here. Enormous slips occur round the basaltic plateau of the north-east of Ireland. The cap of this tableland is a sheet of massive Basalt, seven hundred or eight hundred feet in thickness; beneath this comes Chalk, which rests on Marl or Shale. These lower beds are softened by percolating water, and crushed out by the weight above.

Landslips on a large scale take place on the Dorsetshire coast. The section of the cliffs is—

4. Chalk.
3. Sandstone with Chert. (100 to 150 feet.)
2. Loose incoherent Sand, called Fox Mould. (150 to 200 feet.)
1. Lias Clay (impervious).

The three upper beds are pervious, but the water is stopped at the Lias Clay. The loose Fox Mould is under no circumstances very well able to support the weight of the beds above, and when it becomes full of water it is still further weakened, and portions of it washed out along the face of the cliffs; the dip also is seawards. There is everything, therefore, favourable to the production of landslips, and they occur on an enormous scale.[*]

The picturesque undercliff of the Isle of Wight owes its wild and rugged outlines to the piling one upon another of landslips, which have from time to time broken off from the cliffs and hillsides above. The section of the solid hill face shows—

Pervious.	3. Chalk. 2. Sandstone, Sand, and Sandy Clay. (150 feet.)
Impervious.	1. Gault Clay.

The beds dip seawards, and the surface of the Gault Clay is rendered so unctuous and slippery by the water which reaches it through the overlying strata, that sliding readily goes on. The cause is so obvious that the Gault goes locally by the name of the "Blue Slipper."

The masses detached by landslips are more or less shattered, and hence fall a prey to atmospheric destruction more readily than when they formed part of a solid rock; thus landslipping becomes a very efficient aid in widening those valleys along whose flanks it goes on.

Basin-shaped Lie of Outliers.—One more fact in connection with landslips calls for notice. It will be found to be very generally the case that, where a hilltop is capped by an outlier of rock, the dip is on all sides *into the hill.* The reason of this is that the inward dip hinders the formation of landslips, and so contributes to the preservation of the outlier. An outlier, whose beds dipped from the centre outwards, would, if other conditions were favourable, shed off landslips all round, and would thus be soon carried away altogether. The above rule is so very general, that the mere occurrence of an outlier on a hilltop affords strong presumptive evidence that the beds of the hill lie in a basin.[†]

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[*] See a detailed account of a very large slip at Axmouth, by Messrs. Conybeare and Buckland (Murray, 1840), and Lyell's Principles, 10th i. ed., 536.

[†] Ruskin, Modern Painters, vol. iv. chaps. xiii., xiv.; Topley, Geol. Mag., iii. 438.

Steps in the Formation of the Surface.—Having now seized on the principal result of the action of different denuding agents, let us try if we can picture to ourselves the steps by which a mass of rock formed beneath the sea is converted into a land surface diversified by hill and valley. First came the upheaval, and this we have seen was effected by a bending of the originally horizontal strata into a series of arches and troughs, the former of which gave rise on emergence to tracts of dry land. But the result was not accomplished without a struggle; whenever one of these broad-backed masses reached the surface of the water, it came within the range of marine denudation. The waves attacked it and pared it away,. and, as it was slowly lifted up, slice after slice was planed off the top. Thus a constant battle went on between the two opposing forces, the one striving to raise the submerged mass beyond the reach of the waves, the other wearing it away down to the sea-level as fast as it got its head above water. But at length the up-arching movement gained the mastery, and a tract of dry land was established. Since this land had been formed by the planing away, one after the other, of horizontal slices from the back of the arch, its surface must have been nearly level; but since it owed its existence to a bending up of the beds, it would probably be slightly higher in the middle than at the margins; and the slope either way would be in the same direction as the dip of the beds.

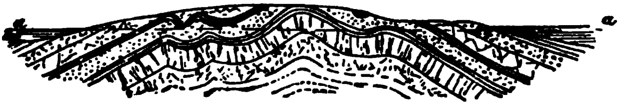

Fig. 110.—Section across a Country after the Formation of a Plain of Marine Denudation.
a a. Sea level.

Hence the surface of the new-born land would consist of two inclined planes, meeting along the crest of the arch, and sloping thence gently down to the sea-level; and the inclination of the surface on either side would be in the same direction as the dip of the beds.

This was the first step of the process, and, when it was completed, a section across the country would be such as is shown in Fig. 110.

The tract of dry land thus established is placed beyond the reach of the sea, only to be subjected to the action of subaërial denudation, and we must next inquire how it will be modified by atmospheric wear and tear. First, rain streams over it, and seizing on any little inequalities becomes collected into channels. Since these channels must follow the slopes, and the ground slopes either way with the dip of the beds, it is easy to see that the earliest watercourses will run in the same direction as the general dip of the country. Moreover, because these channels are formed by river action, they will tend to be trenchlike in shape.

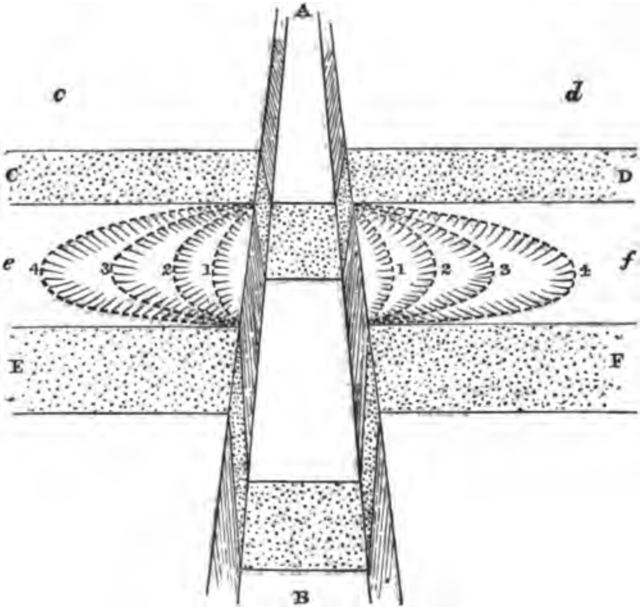

Fig. 111.—Diagrammatic Plan and Section of a River Trench, crossing Strata of unequal Hardness.

N.B.—The bands representing the different strata in the sides of the trench are so violently foreshortened as to give the idea that the beds are vertical. The reader must please bear in mind that the beds are dipping at a moderate angle from A towards B.

The second step then consists in the formation of a series of trench-like river channels running in the direction of the dip.

The valleys thus formed cut *across* the outcrops of the beds, and are hence called *Transverse Valleys.*

Fig. 111 is a bird's-eye view of a country, showing in a diagrammatic form one of these trench-like valleys (*A B*), cutting across the strike of the beds, which come to the surface along the lines *c d*, *C D*, *e f*, *E F*, and dip towards the spectator.

But these first-formed valleys cannot long keep their trench-like shape. Atmospheric action, we have seen, gradually broadens them, and it has been further pointed out that the process goes on much faster in some rocks than in others, so that along the outcrop of certain beds the valley is widened at a more rapid rate than along that of others. Hence arises that alternation of broad valley and strait gorge which is so constant a feature in valley contour; and from a continuation of the same process still more important modifications result, which we now proceed to notice.

In Fig. 111, suppose that *A B* represents a transverse trench, and that, among the beds which it cuts across, *c d* and *e f* are more easily denuded than *C D* and *E F;* the widening of the trench will go on faster in the first pair than in the second; where it crosses *C D* and *E F* the steepness of its sides will be destroyed very slowly, but where its walls are formed of *c d* and *e f*, its edges will be more rapidly worn back, and little recesses will be formed in the face of the trench. The continual washing in of the soft strata will deepen and extend these recesses, and they will creep step by step outwards along the outcrop of such beds, assuming in succession positions such as those marked by the dotted lines 1, 2, 3, 4.

A very little reflection will show that this becomes in the end equivalent to the formation of two branch valleys running along the outcrop of the stratum *e f*, the streams draining which become feeders of the original transverse river.

Here, then, we have arrived at the third step in the process of valley excavation. *It consists in the formation of valleys branching out of the first-formed transverse valleys, and running along the outcrop of the more easily denuded beds.*

The valleys thus formed, because they *follow* the strike, are distinguished as *Longitudinal Valleys.*

We have for distinctness' sake spoken of the three steps, the Formation of the Plain of Marine Denudation, the Excavation of Transverse Valleys, and the Wearing back of Longitudinal Valleys, as having taken place one after the other. In reality the last two, and to some extent all three, go on together. The result, however, will be evidently the same as if each step had been finished before the next was begun.

Valleys determined by Joints.—If there be no great inequality in the rate at which the different rocks yield to denudation, tributary valleys will still be formed, but their position and direction will be determined by some other circumstances. For instance, if the rocks are well jointed, master joints will be lines of weakness, well calculated to be widened by atmospheric erosion, so as to give a start to a line of valley.

Valleys determined by Faults.—Faults, too, in a similar way sometimes determine the lines of valleys. Where hard and soft rocks are brought side by side by a fault, the latter are worn away more largely than the former, and a valley results. Such valleys, like the faults which give rise to them, usually run approximately in straight lines. It must be carefully noted that in such cases faults may be said to produce valleys only in so far as they give rise to conditions which cause denudation to act unequally: they are only the indirect originators. No case is known where the fissure of a fault is a gaping chasm, such as would form a valley without the aid of denudation.

Qualifications.—The somewhat hard and rigid classification of valleys which has been just given, and the explanation which has been attempted of the way in which each kind arose, is of course true only in a very general way. It is a broad and, so to speak, diagrammatic description, in which the main characteristics only are retained, while many minor details and divergences from the general scheme are left out. Thus, there are valleys which are neither transverse nor longitudinal, but have had their directions determined by causes, two of which have been just mentioned, other than the lie of the beds. Other valleys again partake of the character of both kinds, running parallel to the strike for parts of their course and crossing it in other parts. Such valleys can frequently be shown to have arisen in a manner which Fig. 112 will explain. The fine parallel lines represent the outcrops of the different rocks, and *A B C* is a stream, which from *A* to *B* is longitudinal, but at the latter part turns suddenly and assumes the character of a transverse river. In such a case we usually find an upward continuation, *B D*, of the valley, *B C*. This is now so small in comparison with *B A*, that it is looked upon as a tributary; but it is likely that the valley system at first consisted of a transverse gorge only, of which *D B* formed the upper and *B C* the lower part, and that *B A* was originally a longitudinal tributary subsequently formed. The growth of the portions *A B*, *B C*, has however been more rapid than that of *B D*, and hence the latter has become insignificant and sunk to the rank of a tributary, and the original feeder, *B A*, has, on account of its faster growth, reached a size which causes it to be regarded as a part of the main stream.*

Exceptions to our scheme, such as these, doubtless occur; but if they are allowed for, it will be found to be in the main a true and useful classification.

We must indeed bear in mind that in each individual case peculiar conditions give rise to peculiar modifications of the broad character of both valley systems. And when the geological structure is very complicated and has been produced by a long succession of upheavals and denudations, it may be difficult, perhaps impossible, fully to see one's way through the long chain of events that have had a share in the production of the surface; but in very many cases the description just given will be found to apply fairly well to the present arrangement of hill and valley, and traces of the three different processes that have been mentioned as contributing to its formation may still be detected with more or less of certainty.

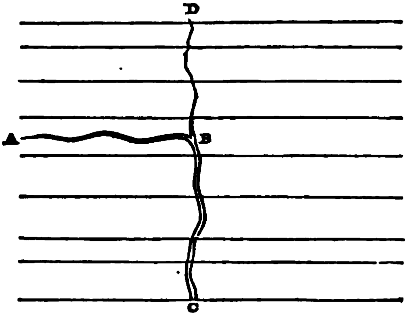

Fig. 112.—Plan of a River Valley, partly Longitudinal and partly Transverse.

Final Results of Subaerial Denudation.—Now that we have formed a notion of the way in which hills and valleys come into existence, we may carry our inquiries a step further, and ask what is the result of the action of subaërial denudation on the features which it creates.

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* This explanation was given by the late Mr. Jukes to account for the erratic behaviour of some rivers in the south of Ireland. Quart. Jour. Geol. Soc., xviii. 378.

As long as rivers have sufficient fall, they continue to cut down their channels; and though the hilltops and plateaus are at the same time being gradually lowered, yet the first process goes on so much faster than the second that the inequalities of the surface continue for a long time to be not only preserved but even increased. But if there be no unequal elevation of the land, there will come at last a time when the continual lowering of the beds of rivers has so far decreased their fall that they are no longer able to deepen their valleys; and when this has come about, each river will meander from source to mouth over a flat raised but little above the sea-level. Atmospheric wear, however, will still continue to act on the surrounding hills and sweep the waste of them into the rivers, which bear it away, and so in time they too will be cleared off. Thus the final result of atmospheric denudation is to destroy the features which itself gave rise to, and the end of its action is to plane everything down to a uniform level. It may be that some of the level surfaces, which seem to have preceded the present arrangement of hill and valley, have arisen from the long-continued action of subaërial wear, and not from marine denudation.

The considerations just stated show that, in the case of an unconformity, the denuded surface of the lower group may have been produced in three different ways. Denudation may have been arrested, by the rocks being again submerged, as soon as the formation of a plain of marine denudation was complete. Or submergence may have been deferred till subäerial wear had cut out hills and valleys. Or, lastly, the older rocks may have remained above water long enough to allow them to be worn down by long-continued subäerial wasting to a flat surface. In the first and last cases the floor on which the newer rocks rest will be fairly level; in the second it will be strikingly uneven, and the upper group will fill up its depressions and level over its inequalities.

Anomalous Behaviour of Rivers explained.—The theory of the formation of valleys just given enables us to account for some very puzzling points in the behaviour of rivers, which may be conveniently stated and explained here.

The anomaly to be got over is this. We frequently find a country traversed by a number of hill ranges running parallel to each other and separated by broad valleys. In such a case we might expect to find the principal streams running along the valleys between each two consecutive ridges. Just the very contrary, however, is the case; the main rivers cut in a most marked way across ridge after ridge, traversing each in a narrow gorge-like valley, and the waters that drain through the valleys between the ridges empty into these trunk streams. To use a common expression, the great rivers run across the "grain" of the country, and the streams that flow with the "grain" are only tributaries; in other words, the principal drainage is "transverse," the tributary streams are "longitudinal." We need not go far from home to find instances. Two such ridges cross in almost unbroken lines the south-east of England: one, formed of a group of hard Limestones, distinguished as the Oolitic formation, extends from Gloucestershire to Lincolnshire; another, composed of Chalk, stretches from Dorsetshire to the coast of Norfolk. A broad plain spreads out to the north-west of the Oolitic range, and another great flat lies between the two ridges. Each of these ridges, too, presents a steep face to the north-west, and falls away with a long gentle slope in the opposite direction. Nothing would seem more natural than that the two hill ranges should act as watersheds—that the brooks streaming down the south-easterly slope of the Oolite range, for instance, should be carried off by a river running at the foot of the Chalk escarpment. Nothing of the sort occurs; a large portion of the main-drainage is carried off by rivers which run directly across one or both of these ranges. Thus the Witham, the Welland, the Nen, and the Great Ouse all rise on the plain to the west of the Oolite range, and each in succession cuts across this ridge and discharges into the Wash. The most marked instance of a transverse stream, however, is furnished by the river which is called the Churwell above Oxford, and the Thames below that city. It springs in the plain to the north-west of the Oolitic escarpment, cuts through that escarpment, continues its course over the flat between the Oolitic and Chalk ranges, and then breaches the latter, cutting across it in a direction almost at right angles to its general trend. A word of explanation as to the case is perhaps required. If we adopt the usual nomenclature of geography, we should say that the Thames rises in the Cotswold Hills, flows in a longitudinal east and west valley to Oxford, then turns suddenly to the south and cuts transversely across the Chalk range. The explanation, however, of cases like this, illustrated by Fig. 112, will apply here. The transverse gorge of the Thames below Oxford is so clearly a continuation of the valley of the Churwell, that we must look upon the two as constituting together the original transverse trench with which the drainage system began; and the portion of the Thames valley above Oxford is as clearly a longitudinal feeder excavated subsequently in the manner already described. As one more instance, we may mention the Stour, which rises on the low ground to the north-west of the Chalk range, and cuts directly across that ridge to enter the sea in Poole Harbour.

Another very striking instance is furnished by the Weald of Kent and Sussex. This is an area surrounded on the north, west, and south by a lofty range of Chalk hills, with their steep sides facing inwards. Starting at Folkestone, we trace this girdling ridge along the North Downs to beyond Guildford; it then bends south, and, afterwards turning east, runs along the line of the South Downs to Beachy Head. Between the last point and Folkestone the coast is low and flat, and there is no barrier separating the interior from the sea. In a district hemmed in in thie way on three sides, and open to the sea on the fourth, we might expect to find the drainage passing away in the last direction and escaping by what seems its natural outlet. But just the reverse is the case. The streams that enter the sea between Beachy Head and Folkestone are few, short, and insignificant; the principal rivers rise in a central dome of high ground and flow north or south, escaping through narrow valleys that breach the barriers of the North and South Downs. Here, again, the trunk streams are "transverse," the feeders "longitudinal." Among the streams that in this way breach the North Downs are the Medway, the Mole, and the Wey; the Arun, the Adur, and the Ouse in the same way set at naught the barrier of the South Downs.

The Isle of Wight again furnishes other remarkable illustrations of the disregard of rivers to the present contour of the ground. It is traversed from east to west by a strongly defined ridge of high ground formed of Chalk, the country both to the north and south being sensibly lower than the ridge. But the ridge is not, as might be expected, the watershed of the island; by far the larger portion of the drainage is carried off by three rivers —the Brading Brook, the Medina River, and the Yar. All of these, notably the last, take their rise near the southern coast, flow steadily northwards, pass through gaps in the Chalk range, and enter the sea on the north side of the island. Instances might be multiplied without limit. Wherever we study the relation of river valleys to the present physical geography of the country they traverse, we find them, big and little alike, playing the same trick, and forcing their way through hill ranges every way calculated at first sight to bar their progress.

The view in Fig. 107 will give an idea of the way in which a range of hills is breached by a river valley. The stream is flowing *from the spectator;* it meanders over a broad undulating country till it reaches the line of bold hills in the distance, which rise like a wall from the flatter ground in front; and then, instead of being turned aside by this barrier, it cuts across it, running on in a narrow gorge.

Such are the facts which we have to explain, and the explanation resolves itself into finding out how the gorges which conduct rivers through hill ranges were formed.

The rough-and-ready way out of the difficulty, generally accepted in the early days of Geology, was that they had been torn open by convulsions. In no instance could this be proved to have been the case, and in most this explanation could be shown to be directly in the teeth of the facts. The strata on opposite sides of the gap exhibit no signs of violent disturbance, and the river may be in many cases observed to flow over a bed of solid, unruptured rock.

Indeed, one explanation alone is admissible: the gap, like other valleys, has been cut out by a river flowing through it.

If this be granted, it is perfectly clear that the river must have begun to run when the surface configuration of the country was altogether different from what it is now. For, suppose we endeavour to take water in an open conduit across the country shown in Fig. 107, from a reservoir in the foreground, on reaching the distant ridge the conduit would have to take a turn and be carried along its foot. A river is only an open conduit, and hence any river that began to run when the surface is such as it is now, must turn aside on reaching the ridge in the same way.

But the explanation will be perfectly easy if we suppose the birth of the river dates from a time when the present inequalities of the ground had not yet come into existence.

If the reader will recall the account given a little way back of the growth of hills and valleys, he will recollect that there was a time when the surface of the country was a plain as high, or somewhat higher, than the top of the ridge. It was then that the river began to flow, cutting, as has been pointed out, a trench across the plain. In the meanwhile atmospheric denudation was at work, wearing down the country on either side, the stream carrying away the waste as fast as it was washed in.

But it must be borne in mind that, though the deepening of the channel could not go on faster in the soft than in the hard rocks, the country at large was worn away much more rapidly in the first than in the second. Where the river ran over a tract of easily denuded rocks, the general level of the surface on either side was lowered nearly as fast as the river channel was deepened, and the result was a stream flowing through a broad flat raised only slightly above its banks. But where a belt of less destructible rock was crossed, the general degradation of the surface went on much more slowly, and from this two results followed. First, the sides of the channel were but slightly modified, so that the valley retained to some degree the trenchlike form with which it started, and remained a gorge or narrow glen. Secondly, in virtue of their superior power of holding out against denudation, these rocks remained standing up in a band of lofty ground above the flat formed by the removal of softer strata.

In this way, by the gradual deepening of the channel of the stream, and the unequal lowering at the same time of the surface along different parts of its course, the broad flat, the hill range, and the gorge were produced by a connected and mutually dependent set of operations.

History of the Idea of Subaerial Denudation.—The theory that all the lesser inequalities of the earth's surface are due to subaërial denudation is now very generally adopted in this country, and is gaining ground among continental geologists. But though this view is by no means new, it is only of late years that it has met with anything like general approbation. Men for long refused to believe that results apparently so great could follow from causes seemingly so insignificant, let them act as long as you will; or rather, they preferred to save themselves the trouble of investigating the nature and capabilities of these forces by attributing the formation of valleys to causes the existence of which was purely imaginary, or to agents which a little inquiry would have shown were totally inadequate to the task. The earlier speculators supposed valleys to be rents and fissures torn open by convulsions, the like of which had never come within man's experience; and, in spite of its manifest contradiction to observed facts, the notion for a long time held, and in some quarters still holds, its ground. Mountain chains were imagined to have risen with a bound from the sea-bed, and thrown off gigantic waves, which ploughed deep into the ground and scattered its debris far and wide as they rushed madly over the country. A step was gained when these wild dreams were abandoned, and it was realised that the inequalities of the surface had been carved out by denudation. But even then only one-half of the truth was seen, for geologists for a long time persisted in attributing the whole of the work to the sea. A very slight amount of observation would have taught that marine denudation tends to efface rather than produce surface inequalities; but the supporters of this view were quite content with a vague idea that the sea had done it, and did not trouble themselves to explain exactly how. Thus a host of vain imaginings was for a long time preferred to the simple explanation to which a study of nature leads us. The whole truth was first thoroughly seized upon by two of the master minds of the science—by Hutton in 1795, and by Scrope in 1826; and the latter, by an appeal to the district of Auvergne, triumphantly refuted the objection that subaërial agents were not competent to perform the task assigned to them. That country has been formerly the scene of volcanic activity on a large scale, and many of the cones are still standing in a fair state of preservation. Now these cones are composed of such friable materials, that submergence beneath the sea would inevitably sweep them away altogether. It is therefore quite certain that the country has never been overflowed by the sea since the eruptions took place, and that any changes in its surface configuration, which can be proved to have been produced since that date, must be due to subaërial action alone. Such changes can be proved to have occurred in numerous instances; for example, Mr. Scrope pointed out cases where an old valley had been dammed across or filled up by a lava stream, and where the barrier had been cut through or the valley excavated afresh. By reasoning of this kind he established beyond demur, in that particular case, the ability of subaërial agents to effect all that the theory requires of them; and what they can do in Auvergne, they are just as well able to do everywhere else.

SECTION III.—HOW THE CHARACTER AND LIE OF THE UNDERLYING ROCKS AFFECT THE SHAPE OF THE GROUND.

We have already had to notice that the relative power of rocks to resist denudation is an important element in determining some of the leading features of the surface. In this section we will treat this part of the subject more fully.

Relative Hardness.—The character which exercises more influence, perhaps, than any other in this aspect is relative hardness and softness. Hard rocks are able to hold out against the wearing action of denudation better than soft rocks. Hence districts formed of hard rocks stand up more or less boldly and ruggedly in high ground. The country occupied by softer rocks is lower, tamer, and more uniform in outline. This is well brought out in Fig. 113, which shows the main features of the country along a line from Snowdon to the east coast of England.

On the west rises the mountain district of North Wales, formed of old, very much hardened rocks, named Silurian. Then follows a broad, gently undulating tract of low ground occupied by softer strata, known as the New Red Sandstone, which have been only slightly tilted from a horizontal position. To the east of this plain a boss of lofty ground marks the position of the Derbyshire hills; these owe their elevation to the fact that they are composed of a hard group of rocks, known as the Carboniferous, which have been brought up from beneath the New Red Sandstone in a broad anticlinal fold. Descending the eastern flank of the Derbyshire plateau, we find its beds dipping beneath the New Red Sandstone, and pass on to a flat identical in character with that formed by the same formation on the west. After a while the New Red Sandstone begins to be covered up by other formations, known as the Oolitic and Cretaceous; and where the harder rocks of these groups come to the surface, the ground rises into long terraced ridges. The section shows three tracts of lofty uneven ground, and two districts of low and flat ground; and in each case elevation and ruggedness go along with hardness in the underlying rocks, and a low level and evenness of outline with a substratum of soft rock.

The view in Fig. 106 also illustrates this general truth; the softer rocks in the foreground give rise to a low undulating tract; while the hard limestone stands up in a line of bold hills.

Another very striking instance of the way in which hard rocks give rise to projecting eminences is shown in Fig. 114, which is a view of two hills called Park and Chrome Hills, near Longnor, on the borders of Derbyshire and Staffordshire. Here the main mass of the Carboniferous Limestone rises at a steep angle from beneath a body of very much softer Shale, and forms a table-land, the face of which overlooks like a wall the flat country occupied by the Shale; in fact, what we usually get along the line of junction is just such a view as is shown in Fig. 106. In the case now before us, however, this very simple type of landscape is diversified by the presence in the middle of the Shale flat of the two conspicuous peaks shown in the sketch. A portion of the limestone wall is seen in the background, and well in advance of it the hills stand up like outworks in front of a rampart. I can recollect being very much puzzled, when I first saw these hills from a distance, to account for their isolated position, but a closer examination made all clear. Each con-

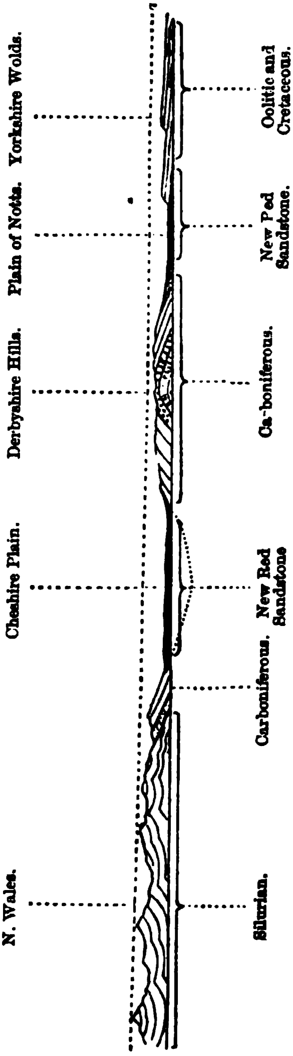


Fig. 113.—Section from Snowdon to the Wolds of Yorkshire.
a a. Plain of Marine Denudation.

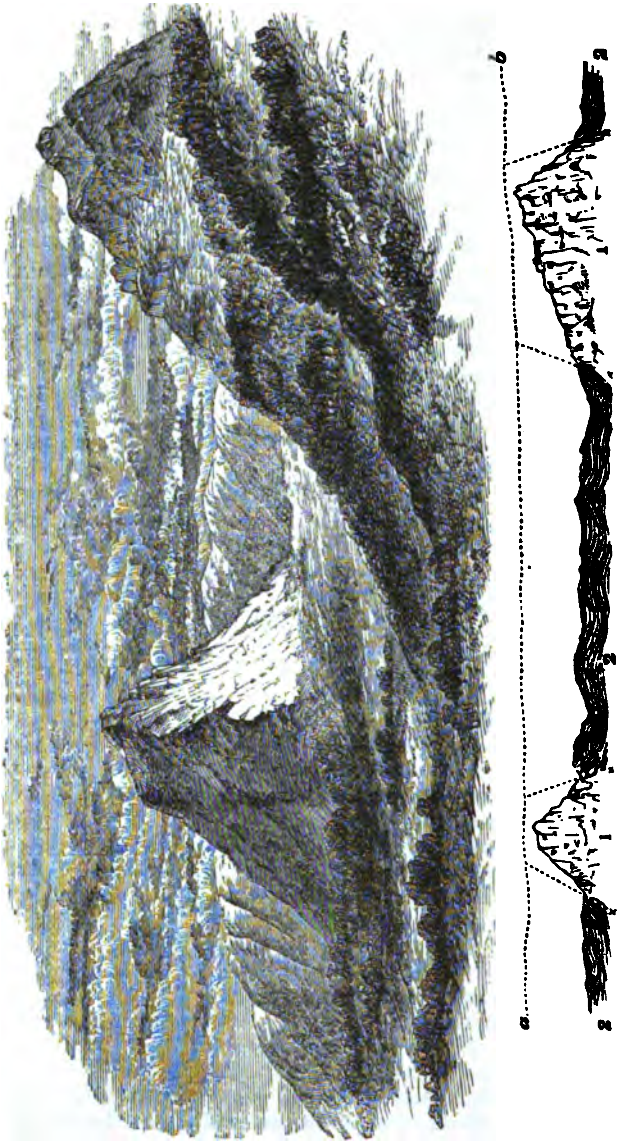


Fig. 114.—View and Section of Park and Chrome Hills, near Longnor.
1. Limestone. 2. Shale. x x. Faults.

sists of a mass of Limestone, roughly triangular in plan, which has been brought up by faults in the middle of the Shale. The soft rock has been washed away by subaërial wear all round, and two pyramid-shaped eminences of Limestone have been left standing up. At the bottom of the figure there is a section across both hills; the surface, when subaërial denudation began its work, may have been somewhere about the dotted line *a b*; all between that line and the present surface has been removed, and it is easy to see that the occurrence of the two isolated hills is due to the fact that the soft Shale has been carried away to a much larger extent than the hard Limestone.

Other Qualities which enable Rocks to resist Denudation.—But it is not always the hardest rocks that best resist denudation; Chalk, for instance, is by no means a hard rock, but it stands up boldly in conspicuous hills above Clays almost, if not quite, as hard as itself, in a way that shows that it has something about it which enables it to hold its own against the wear and tear of atmospheric agents better than the Clays. Probably the property which produces this result is the extreme porousness of the rock—all the water that falls upon it is at once sucked in, and there is scarcely any flow over the surface to produce erosion; the Clay, on the other hand, which has suffered so much more largely, admits no water, and hence a large portion of the rain which its surface receives is available for denudation. There is a fact pointed out to me by Mr. C. E. Homersham which bears out this view. When we pass off the Chalk on to the adjoining district of London Clay, we find that the bridges become all at once larger, and that where a road crosses a flat liable to floods the flood-arches are more numerous and wider. The contrast is very striking, and proves how much larger the surface-flow of water is over the latter rock than over the former.

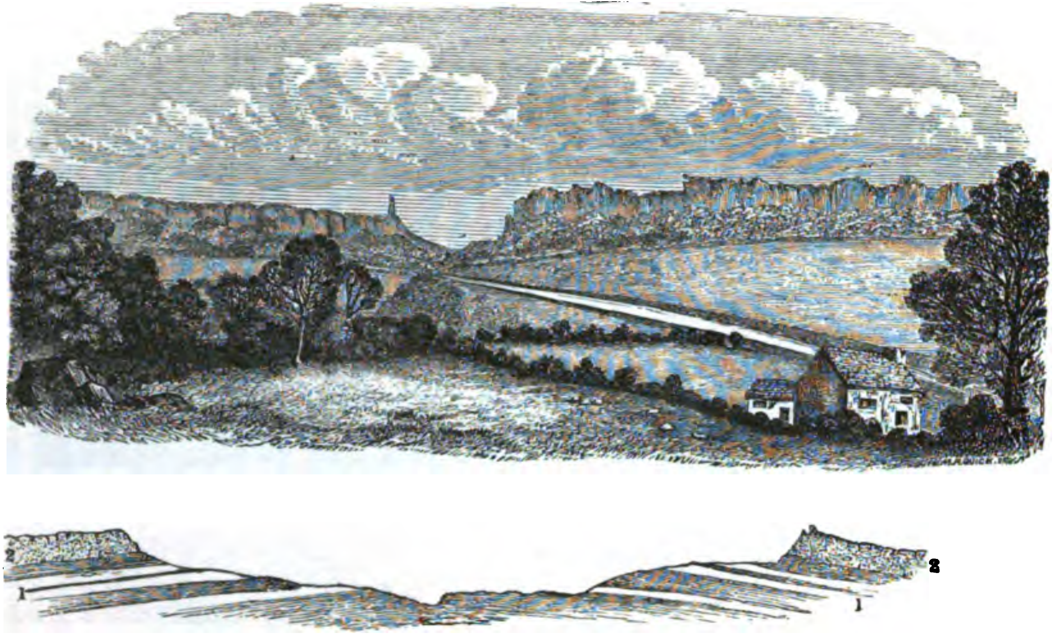
Another illustration of the principle we are now considering is furnished by the section on Fig. 113. It will be noticed that there is a slight depression in the middle of the Derbyshire hills; the boss is higher at the edges than in the centre. But the rock which comes to the surface over this sunken space is by far the hardest of the group that makes up the high ground. The probable reason why it has not the superior elevation to which its hardness would seem to entitle it, is that it is a Limestone, and therefore is dissolved away chemically as well as worn away mechanically, while the beds above it are Sandstones, whose destruction is mainly effected by mechanical means alone.

Examples like this teach us that the rock which makes the boldest feature is not necessarily the hardest, but the one which can best resist denudation, to whatever quality that power is due.

Difference between Results of Marine and Subaerial Denudation.—So far we have dealt mainly with denudation in general in this section; but it is instructive to note how the results, which depend on the qualities we have been considering, vary according as the agent employed is the sea or subaërial forces. The effects of marine denudation are seen in the shape of the coast. It cuts *horizontally*, and those rocks which are best able to resist it, show their power by *running out* into promontories and headlands, while the more yielding strata are worked back, and give rise to bays and inlets. Subaërial denudation acts on inland districts, and cuts *vertically;* and by it the easily denuded rocks are worn *down* into plains and valleys, while the strata which give way less readily *stand up* in hills and ridges.

Both cases are seen side by side in the Isle of Wight. If the reader turns to a geological map of the island, he will see a belt of Chalk, a rock which we have seen resists denudation, running across the middle of it from east to west; the rocks overlying the Chalk to the north, and those underlying it to the south of the belt, are both of a more yielding character. The Chalk shows its superior powers of resisting the *horizontal* planing of marine denudation, by *jutting out farther to sea* than the beds above and below it into the bold headlands of Culver Cliff and the Needles. Inland it gives proof of its ability to hold out against the *vertical* action of subaërial denudation, by standing up *higher* than the beds on either side in a bold ridge, that stretches athwart the island between these two projecting points.

Effect of Natural Planes of Division.—Joints and other natural planes of division exercise an important influence on the shape of the surface. They admit water, and determine the lines along which it acts with greatest efficiency; and when their fluid contents are expanded by frost, it is along them that portions break off. Hence, in well-jointed rocks, valleys will tend to become gorges and hillsides to become precipitous. This is well illustrated by the view in Fig. 115, which represents a valley in the Millstone Grit district of Derbyshire. The bold line of mural



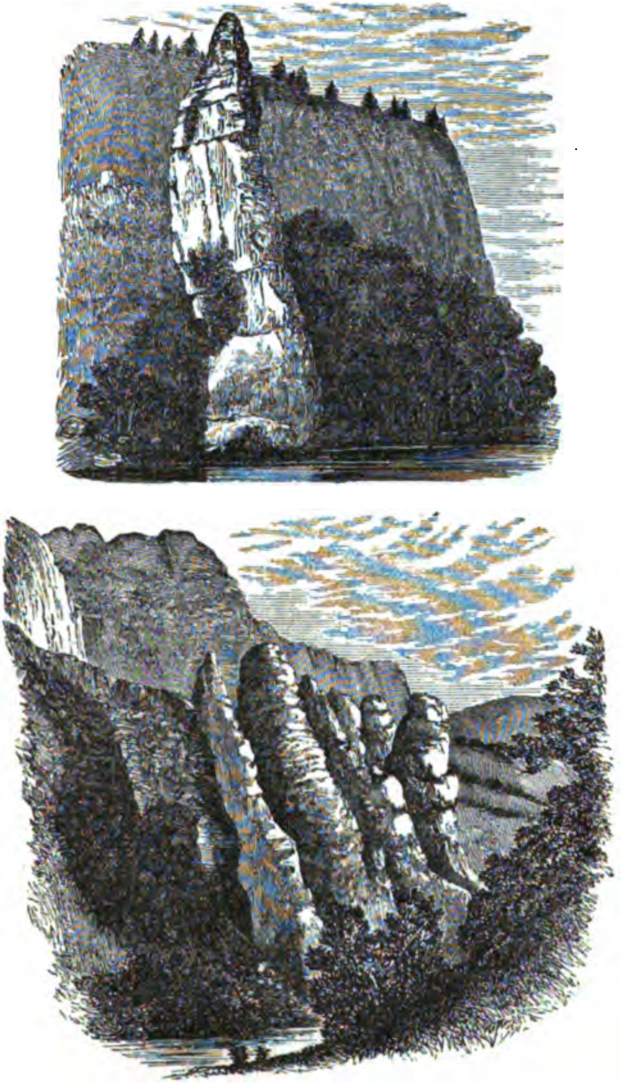
Section across the Valley.

Fig. 115.—View looking up the Valley at Baslow, in Derbyshire.

2. Hard, well-jointed Grit. 1. Soft Shale and Sandstone.

precipices which crown the flanks on either side are composed of a hard Gritstone, while the gentler slopes below are occupied by softer alternations of Shale and Sandstone. This difference in the character of the rocks would alone lead to considerable difference between the inclination of the upper and lower parts of the sides of the valley; but the cliffs at the top owe their marked steepness and buttressed face to the fact that the capping rock is traversed by two sets of long regular joints, nearly at right angles to one another. As the Grit is undermined by the weathering out of the soft underlying beds, portions become deprived of support and break off along these joints, and hence the upper part of the hillside assumes the form of a vertical cliff, the face of which is from time to time renewed, and kept always sharp and clean. That this is the method of the formation of the feature is clearly seen when we examine the sides of the valley. At the foot of the present cliff we find a talus of blocks which have evidently been detached very recently; but these proofs of the work of destruction are not confined to this part of the hillside; the slopes all the way down are thickly strewn with huge masses of grit, perfectly angular, and, except that they show a little more signs of weathering, in every way similar to the freshly fallen blocks at the top. These, there can be no doubt, are the ruins of old escarpments, and indicate successive positions of the cliff while it was being worked back to its present line. These loose blocks are so numerous that they furnish ample materials for walls and buildings, and do away in great measure with the labour of quarrying. They are distinguished from the stone raised in quarries by the name of "Day-stones."

It is denudation, guided by natural planes of division, that has given rise to the isolated pinnacles of rock that occur so frequently both inland and on the sea-coast. We have chosen two instances, one formed by subaërial, the other by marine denudation. The first, shown in Fig. 116, is a tall spire of Limestone standing in one of the Derbyshire dales. Fig. 117 shows the way in which it was formed: the rock is traversed by two sets of joints; carbonated water passing through these dissolves the Limestone and widens the fissures. By the enlargement of one set of joints a number of buttress-shaped projections jutting out from the hillside are produced. A similar operation acting along the other set of joints cuts up these buttresses into pinnacles. Some of the buttresses shown are in the first



Figs. 116 and 117.—Detached Pinnacle and Buttresses of Limestone, Derbyshire.

stage, the most distant has already begun to be subdivided into pillars.

Our other instance is the Needles of the Isle of Wight. The Chalk, of which these are composed, has been tilted till its beds are nearly vertical, and it is also traversed by joints perpendicular to the bedding. The waves, aided by subaërial agents from above, have worked their way along these two planes of division, and severed several blocks of the rock from the main mass in the cliff. The faces on which the light falls are formed by planes of bedding, the slight deviation of which from the vertical gives the Needles their overhanging position; the faces in shadow are joints.

Effect of the Lie of the Beds on the Shape of the Surface.—It is easy to see that the inclination of the beds is an important element in determining the shape of the ground. Consider two areas of equal extent, over one of which the beds lie flat, while in the other they are inclined to the horizon. In the case of the first, when marine denudation ceased to act, the surface was formed everywhere of the same rock; it would therefore *be lowered everywhere at the same rate by subaërial denudation*, and the result would be a sameness of feature and a tendency to the formation of a plain or table-land. If the rock composing this flat is hard, the valleys cutting across it will keep a narrow, steep-sided cross-section, will be trenches in fact that from a broad point of view will not interfere with its general plateau-like character; but if the underlying rock be soft, the river trenches will be gradually opened out into broad valleys, and this widening may go on till the plateau-like character of the ground becomes entirely destroyed, and its former existence can only be inferred by noting that the ridges separating the valleys are all very nearly of the same height.

If we now turn to the other area, where the beds are tilted, we see that the surface is formed of a succession of rocks, differing in hardness and other qualities; it will therefore be *lowered unequally by subaërial denudation*, and the result will be variety of feature and a tendency to the formation of hills and valleys.

Escarpment and Dip-slope.—Such are the broad general facts. When we come to examine more in detail the shape and character of the features of a country composed of alternations of hard and soft rocks dipping at moderate angles, we find them to be as follows. The outcrops of the harder strata are marked by ridges running

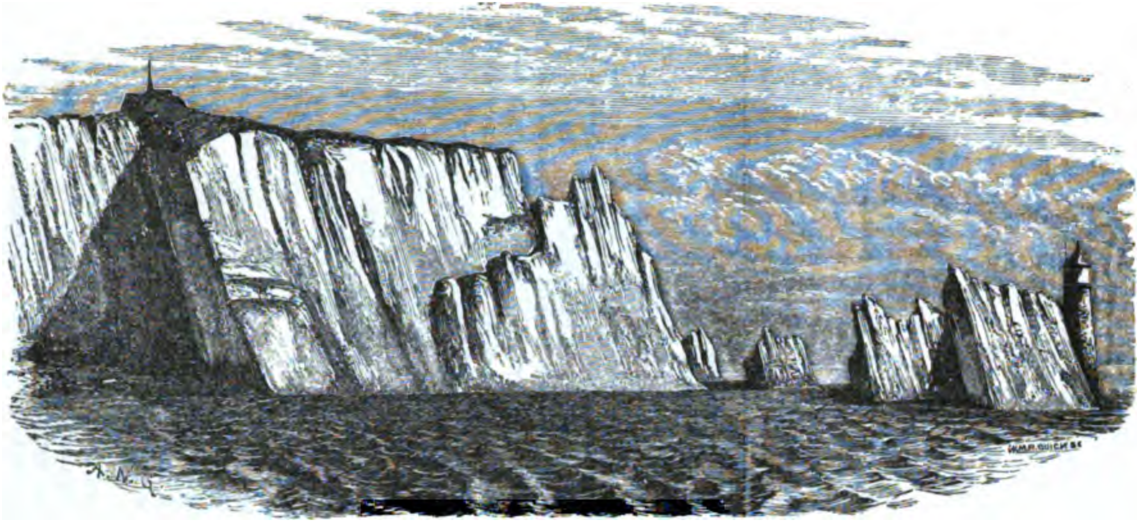


Fig. 118.—The Needles, Isle of Wight.

parallel to the strike; the ground occupied by the softer beds forms valleys or plains. Further, there is in most cases a marked difference between the slope of the two sides of a ridge formed by the outcrop of a hard member of a group of bedded rocks. On one side it presents a steep or vertical face, on the other it falls away in a long gentle incline. The next thing we notice is that the steep faces are all turned one way, and the gentle slopes all the other way; the first all look towards the quarter to which the beds rise, the latter are inclined in the same direction as the dip, and frequently at almost the same angle. Hence the latter go by the name of ***Dip-slopes***, while the steep sides are distinguished as ***Escarpments***.

In the view and section in Figs. 119 and 120 we have a very marked instance of the kind of feature just described. There are two ridges running roughly parallel to one another, and in each the side turned away from us is steep, and the side facing us is a broad flat surface, sloping gently down towards the spectator. The section shows how these features are related to the lie and character of the rocks; it runs from the highest point of the distant ridge across the summit of the nearer ridge on which a group of trees is perched. We see at a glance that the steep fronts look in the direction of the rise of the beds, and that the long gentle slopes fall away in the same direction as their dip, and nearly with the same inclination. Further, the rocks which form each escarpment (2) and (4) are hard Sandstones; and beneath each of these lie more yielding Shales (1) and (3), over the outcrop of which the slope becomes more gentle. The dip-slope of the more distant ridge is broad and very conspicuous, that of the nearer ridge, though narrower, is remarkable for the singular evenness of its surface. The bed (4) is a somewhat massive and well-jointed rock, and hence the escarpment formed by it is abrupt and craggy.

The facts just described are strictly in accordance with the theory already put forward as to the origin of surface inequalities. It was shown that, when a transverse trench had been cut across a plain of marine denudation, its sides would be worn back wherever it crossed a band of easily denuded strata, and in this way longitudinal valleys would be formed running along the outcrop of the softer rocks. The valleys in the present instance are longitudinal, for they follow the outcrop of the belts of soft shale, and they are found to empty themselves into transverse streams. Let us look a little more closely at the steps by which this very characteristic outline has been produced. Let Fig. 121 represent a portion of one side of the transverse trench, the dotted line at the top being the surface of the plain of marine

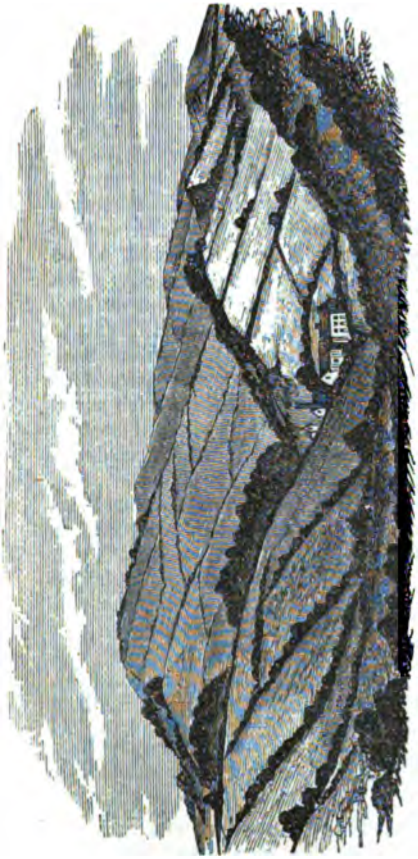


Fig. 119.—View of Escarpments and Dip-slopes.

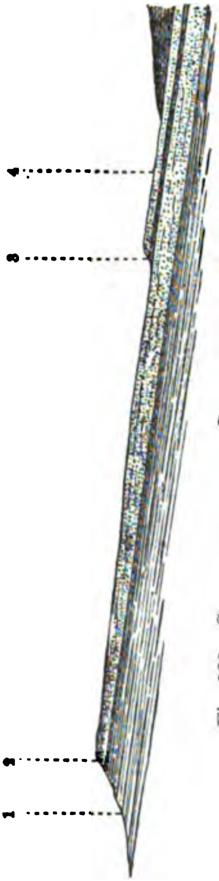


Fig. 120.—Section across the Country shown in Fig. 119.
1. 3. Shales. Soft. 2. 4. Sandstone. Hard.

denudation. Let (1) and (3) be hard, (2) a soft rock. Suppose *A C B* to be the commencement of one of the longitudinal valleys. The stream at the bottom of this will be constantly cutting down, and atmospheric action will be con-

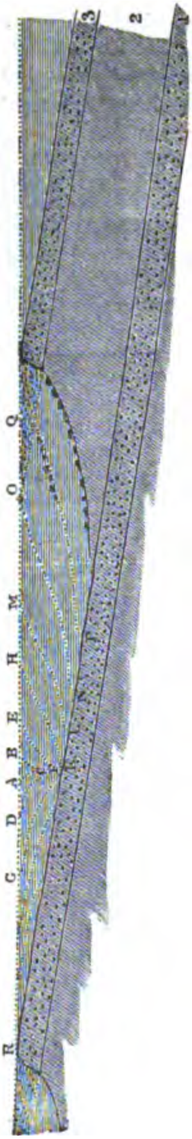


Fig. 121.—Diagram to illustrate the Formation of Escarpments and Dip-slopes.

stantly washing in its banks, so that it will be continually getting deeper and wider, and will assume in succession positions such as *D F E*, *G K H*. The gradual growth of the valley will continue to go on in the manner just described till it has cut down to the top of the hard bed (1), a position indicated on the diagram by *G K H*. This may be called a critical point in the valley's existence; the circumstances under which its excavation has been so far carried on are now altered, and a corresponding modification in the results of the work may be expected. Two courses, so to speak, are now open to the stream: it may go on cutting deeper, but if it does, it will have to work its way through the hard rock (1); or it may attack the bank, *K H*, of soft rock. The latter is so much the easier, that it is evident it will be the one adopted; the direct deepening of the channel will cease, and the running water will expend its energy in undermining the bank on the right hand. Portions of this will thus from time to time be brought down into the brook, where they will be ground fine and swept away. In this way the bank to the right will be continually worked back, and the valley gradually widened, its floor being always formed by the top of the hard bed (1). The action of the stream alone would produce a steep cliff on the side we are considering, but atmospheric wear will come in to modify this result, and, by incessantly breaking down the face, will always keep the slope moderate. Thus, one flank of the valley will be continually shifting to the right, assuming in succession positions such as *L M*, *N O*, *P Q*. When the movement has extended up to the hard bed (3), the upper part of the hillside will, on account of the superior hardness of this rock, stand at a steeper angle than the ground below, and hence an escarpment will be formed at the outcrop of this stratum. We must further notice that the manner in which the slope is worked back will be somewhat different in those parts which are composed of hard rock and in those where the softer beds occur. The latter are gradually washed away bit by bit in a fine state of division; from the former large blocks are detached from time to time, which, on account of their superior power of resisting the action of the air, are broken up very slowly, and consequently remain in large numbers strewn over the slope. As the soft rock on which they rest is worn away from beneath them, these fallen masses slide down lower and lower, till the whole hillside becomes thickly covered with them. One case of this kind has been already noticed (p. 438), and it is an occurrence very frequently met with on the slope beneath an escarpment of hard rock.

While all this has been going on on the right, atmospheric denudation has not been idle on the left-hand side of the valley. The mass *G K R* of soft rock is gradually washed into the stream, and its ruins carried away. This easily destroyed portion the subaërial denuding forces clear off without any difficulty, but they can make only very slight impression on the harder bed below; hence, when the bottom of the valley has been brought down to the top of this rock, any further lowering goes on very slowly, and it remains very nearly at this level. And so in the end we have left of the rock-mass we started with only that part which is distinguished by a darker tint on the figure.

The valley has now assumed a form exactly corresponding to that depicted on Figs. 119 and 120; it has a long dip-slope nearly coinciding with the top of the hard bed (1), and a steep face on the other side; the slope of the latter being comparatively gentle where it is formed of the soft stratum (2), and rising in an abrupt scarp where it is capped by the hard rock (3.)

The reader must not suppose that the explanation just given is pure theory. If he will go into any district where rocks alternately hard and soft rise to the surface, he will not only find numberless instances of escarpments and dip-slopes, but he will see the process to which their formation has been attributed still in action. He will have no difficulty in lighting on cases where a brook runs from some distance exactly along the top of a hard rock with a cliff of the overlying softer beds forming one of its banks. If in such a case he mark the raw newly-cut look of the cliff and the heaps of fallen debris at its foot, he cannot fail to conclude that the stream is undermining its bank, and that, by this gradual working back of the lower part of the slope, aided by subaërial wear above, the valley is being widened, while its peculiar type is all along preserved. Only suppose that the stream has been doing for a long time back exactly what it is doing now, and we have all the machinery necessary for carving out of a plain of marine denudation just such hills and valleys as the landscape sets before us.

In the illustration chosen, the arrangement of the features in escarpment and dip-slope is marked with singular distinctness. The reader must not expect to find many instances which conform to the normal type as rigidly as this. The two distinctive features are often masked to some extent by numerous minor modifications, but they can always be recognised with more or less of certainty in a country formed of bedded rocks of unequal hardness and inclined at a moderate angle. There is probably no agent so efficient as Ice in obscuring the features produced by the unequal yielding of different kinds of rock to denudation. In some tracts, parts of the Carboniferous districts of the North of England for instance, where there are all the requisites for the formation of escarpments, we find these ridges either conspicuous by their absence, or at best far less strikingly marked than among the corresponding rocks of the Centre of England. The explanation probably is, that the more northern region has been swept over by an ice-sheet, which planed down all the lesser inequalities of the ground, and there has not been time since the glaciation for subaërial denudation to carve them out afresh. The ice-sheet probably never reached so far south as the centre of our island, and there the results of long ages of uninterrupted subaërial wear are seen in the conspicuous character of its escarpments. The deposits also formed by ice action frequently prevent our seeing features which actually exist. Sometimes large tracts of country are deeply buried in Boulder Clay, and the uneven surface of the stratified rocks is simply smothered; sometimes masses of Boulder Clay are piled up against the steep face of an escarpment, or moundy hills of the same deposit stand on a dip-slope, and in this way the distinguishing characteristics of each feature are destroyed to the eye. If the driftless area of the Carboniferous rocks in South Yorkshire be compared with the drift-covered corresponding area of Lancashire, the contrast between the sharp definition of the features of the one, and the indistinctness and faintness of the features of the other, is very striking.

Broadening of Valleys by River Action.—In the explanation of the formation of escarpments and dip-slopes, we had an illustration of the way in which a valley of great width may be cut out by the gradual working of a stream of very moderate size. In many other cases rivers have excavated valleys, which at first sight seem out of all proportion to their size, by similar artifices. The great breadth, for instance, of many river valleys in the lower part of their course is mainly due to the incessant shifting of the bed of the stream. The river swings from side to side, attacks first one bank and then another, and by the joint action of its undermining below and subaërial wear above, the sides of the valley are worked back, and widening incessantly goes on.

Cutting back of the Channels of Rivers.—We have hitherto dwelt mainly on the action of rivers in lowering their beds, we have now to look at work they do in a somewhat different direction. In many cases, owing to the unequal hardness of the rocks over which they flow, they are enabled to cut back and lengthen the gorges in which they run. The nature of this action, and the way in which it is carried on, will be understood by a reference to the sketch in Fig. 122.

We see there a brook flowing in a narrow gorge, which is shut in at its upper end by a cliff, over which the water tumbles in a little fall. The upper part of this cliff is formed of a bed of rock which projects well above the strata below; the same bed is seen jutting out here and there among the foliage in prominent ledges from the sides of the ravine. This rock evidently stands out because it is harder than those underneath it, and this is specially the case at the waterfall, because the spray is there always playing on the face of the cliff and aiding other subaërial forces to wear away the soft rocks of its lower part. Whenever the ledge at the top has been in this way sufficiently undermined, a slice breaks off along a joint, and an even face is produced. Undermining then begins again, till another fall of the capping rock results. At the foot of the cliff a pile of freshly fallen fragments shows that the process is always going on. Thus the waterfall, which has in the lapse of time travelled along the whole of the ravine, is still moving in the same direction, and the gorge is being continually eaten farther and farther back.

Instances of this phase of river action may be seen in every mountain brook that flows over alternations of hard and soft rocks. The grandest case known is that of Niagara, so well described by Lyell.*

It is evident that by the action just described very important modifications in the surface-form and drainage-system of a country may be brought about. A trifling rivulet streaming down the face of a ridge may deepen, and at the same time eat back its channel, till a deep valley, cutting completely through the range, is produced. Thus a transverse feeder to a longitudinal valley might spring into existence, from which longitudinal branches would extend themselves; indeed, while it is likely that the great transverse valleys have been carved in the manner already described out of the original plain of marine denudation, we may reasonably refer the lesser valleys of the same class to this cutting-back process.

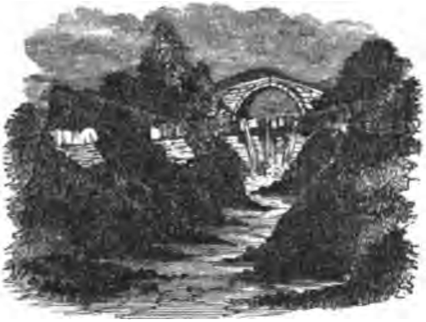


Fig. 122.—Brook cutting back a Ravine.

It is not difficult to conceive, too, how, when a ridge has been cut across by the gradual working back of a ravine, a very trifling amount of unequal upheaval might reverse the direction of the drainage, and turn streams into this new channel which had previously discharged themselves by different outlets.

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* Principles of Geology, 10th ed., vol. i. p. 358; Travels in North America, vol. i. chap. ii.

The cutting back of river channels is not confined to districts where the rocks are of unequal hardness, though it is in such that it goes on most rapidly; it happens more or less everywhere, and must take place largely in rocks, like limestone, which are chemically soluble. The brooks, for instance, that flow down the dip-slope of the Chalk range, push their heads yearly higher and higher up the incline, and may in the end give rise to valleys cutting quite through the ridge, which may carry off much of the drainage of the flat country beyond.

SECTION IV.—FEATURES DUE TO THE ACTION OF ICE.

We have already had to do with the denuding action of ice, but only in so far as it furnishes materials for the formation of Derivative rocks; we will now inquire into its effects on the shape of the surface.

We saw that ice-sheets and glaciers are always moving slowly from higher to lower levels, and that, as they move, they wear away the rocks over which they pass, by means of the stones frozen into their under surface.

The shape given to the face of a country by this grinding action is totally different from that produced by any other denuding agent, and therefore calls for special notice in the present chapter.

But ice-worn surfaces have a further interest for the geologist. Changes in climate may cause ice to disappear, but the markings it impressed on the solid rock survive long after it has passed away; and the observer, when he has once learned to recognise their distinctive character, infers from these surface-forms the former presence of an ice-sheet and the path it took, as readily and as certainly as the hunter draws corresponding conclusions from the footmarks and trail of an animal. In this way we are enabled to show that countries which now enjoy a temperate climate, were once placed under conditions such as now prevail only in Arctic regions.

General Aspect of Ice-worn Districts.—A sheet of ice, as it flows over a country, wears down all projecting points, and smooths off all rough places, and in this way the hills of an ice-worn tract get a general rounded hummocky outline. No words can give an adequate idea of the appearance of such districts; but any one who has stood in the middle of a group of lofty hills formed of bare rock, where ice-work has gone on on a large scale, never forgets the wonder with which he for the first time gazed on the sameness of the flowing contours which every hill offered to the view. It is as if some giant hand had taken sheet after sheet of emery paper, and rubbed and ground away till every prominent peak and bristling crag had been cleared off, and every valley-side smoothed down. The view in Fig. 126 will, perhaps, give some faint notion of the peculiar aspect of such a landscape; the hills on the left-hand side of the lake are strongly typical.

In some cases this smoothing extends itself over the tops of the highest hills, and furnishes proof that the whole country has been wrapped in one universal mantle of ice, like Greenland and the Antarctic continent at the present day. Elsewhere the ice-worn surfaces are confined to the valleys, and extend only to a certain height up the hill-sides, in which case the glaciation was less extensive, and the ice took the form of glaciers. The observer must not, however, jump too hastily to the conclusion that he has determined a line above which the ice did not rise, merely because he finds traces of its action plentiful on the lower part of the slopes and apparently absent on the hill-tops. Ice-tracks of course suffer, and are in time completely removed, by denudation; they will evidently weather away faster on exposed summits than in lower and more sheltered spots, and this may be the explanation of their absence above a certain elevation. But if we find a fairly hard line, below which the ground is very generally smoothed, and if above that line it is rugged and bristling, and does not yield to the most careful search the faintest remnant or trace of ice-worn patches, then we may be pretty sure that that line marks the upper limit of the ice.

Polished Surfaces.—The features just described are those which strike the eye on a general view of an ice-worn country. The minor details, which closer examination reveals, are no less remarkable and no less important geologically.

Rock surfaces worn by modern glaciers have frequently a polish as perfect as could be produced in a lathe; and similar surfaces of very ancient date, when they have been protected from the air by a coating of clay or other impervious material, are found to have lost scarcely any of their original high polish.

Scratches.— We have already explained that the tools

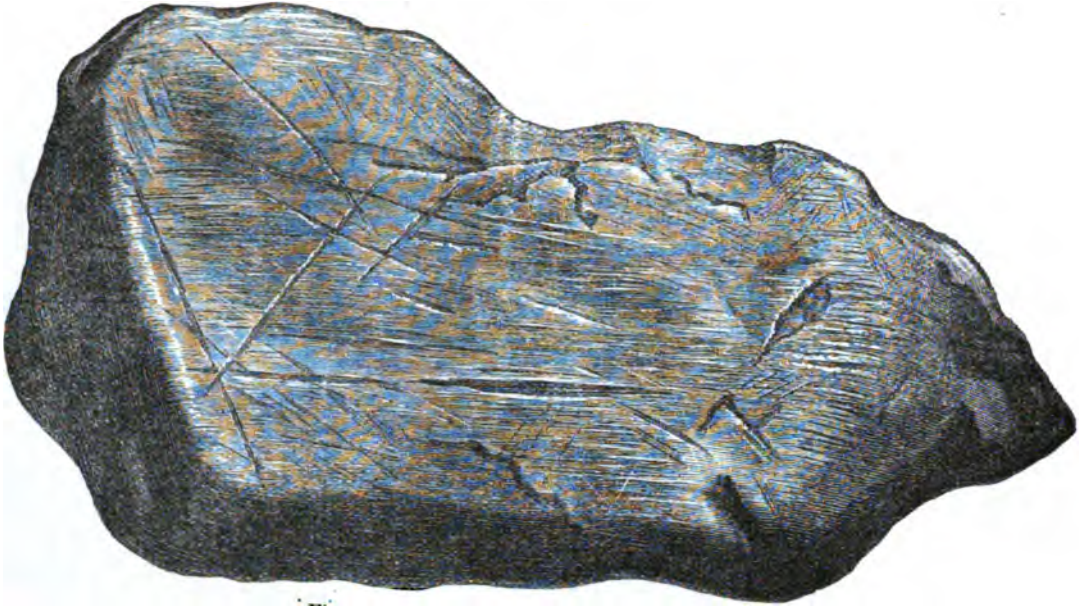

Fig. 123.—BLOCK OF ICE-SCRATCHED LIMESTONE.

which enable ice to grind away the rocks over which it passes, are stones frozen into its under surface. The high polish just mentioned is produced by fine sand; stones cut grooves or striations according to their size, the small sharp points etching on the rocks scratches as fine as the most delicate work of a steel engraving, the larger blocks ploughing out flutings and coarse ruts. Fig. 123 shows a stone on which both fine and coarse striæ have been impressed.

These markings are of the utmost value. The scratches on the stone figured above will be noted to be rudely parallel to one another, and this general direction is evidently that in which the ice flowed. By observing and recording the bearings of similar scratches on rocks in place, we shall be able to lay down the line of the path which the ice that made them, took across the country. Also the relation of the scratches to the surface will enable us to form an idea of the extent of the glaciation, and to say whether it amounted to a universal ice-sheet or got no further than valley glaciers. In the first case, the enormous accumulation produces a pressure sufficient to drive the ice from the interior to the coast, not exactly in straight lines over hill and across valley, but still with considerable disregard to the inequalities of the surface; the scratches in consequence radiate in a general way outwards, from the centres of maximum elevation, and frequently pass up the sides and across the summits of the hills. In the case of glaciers, the motion of the ice, and the scratches which it cuts, are parallel to the trend of the valleys.

Roches Moutonnées.—From the grooves and scratches just described, we can lay down the course of the ice's motion, but they do not tell us which way it travelled. We can learn, for instance, that its path lay north and south, but not whether it came from north to south, or in a contrary direction. This information we gather from the shape of certain rounded hummocks, always found in glaciated districts and called Roches Moutonnées.

Fig. 124 is a sketch of one of these; and it will be noticed that while the right-hand side rises from the ground with a gentle, smoothly-rounded slope, the front is steep and comparatively unworn.

If we examine a valley still occupied by a glacier, but in which the ice formerly extended lower down than now, we shall find that the gentle slopes of all the moutonnéed bosses look up the valley, and their steep fronts all face the opposite way; since the motion of the glacier is down the valley, this amounts to saying that the smooth faces point to the quarter from which the ice comes.

Similarly, in a country from which ice has completely disappeared, if the moutonnéed surfaces are preserved, we learn from them in what direction to look for the source of the ice.

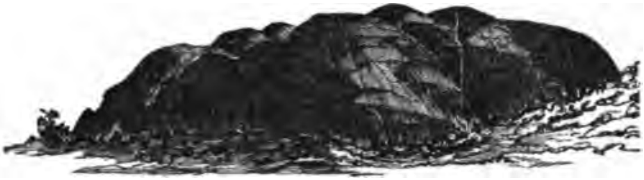

Fig. 124.—Roche Moutonnée.

It is easy to see how this peculiar form came about, and why the opposite faces of the hillocks are so different. Let the line *S S* in Fig. 125 represent the rugged surface of a rocky country over which a sheet of ice is moving in the direction of the arrow. As the ice is driven up the slope *A*, it will grind away all the inequalities, and work the surface down to an even rounded outline. The debris produced will be pushed on over the crest, and fall down on a bank in front of the hillock. The ice, as it moves on, will ride over the top of the heap, and not touch, or touch to a very small extent, the face *B*, which will therefore retain its roughness. Where the ice impinges on the next projection of rock, the face which it meets will be worn smooth, and the opposite side will be protected by debris, and be little affected. In the end, when the ice

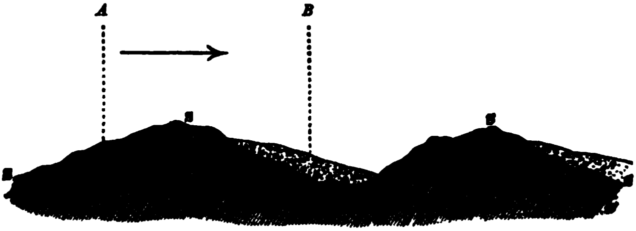

Fig. 125.—Diagram to illustrate the Formation of Roches Moutonnées.

has gone, and the loose debris has been removed by denudation, there will remain only the part tinted dark in the figure, that is to say a couple of hummocks with the outline which has been described as characteristic of roches moutonnées.

Moraines.—The moraines of vanished glaciers are as important as the traces of ice-action already mentioned, whether we look upon them as features in the scenery or as a means of enabling us to read the history of former glaciations. Longitudinal moraines remain as long lines of hummocky mounds or ridges running *along the sides* of valleys; terminal moraines have a similar outline, but stretch *across* the valley in a horse-shoe-shaped curve, with its convexity pointing downwards. The latter have frequently suffered largely from denudation, but, where they are well preserved, they sometimes furnish an elegant proof that the glacier which gave rise to them dwindled away little by little before it finally disappeared. It is not uncommon to find in the upper recesses of mountain valleys a series of small terminal moraines, one within the other, each one more puny than the one below it. From these we learn that, after the ice had disappeared from the low country, glaciers still held their own in the uplands; but that, as the climate improved, they shrunk back higher and higher up the valleys. Each moraine marks a line at which the glacier paused for a while in its retreat, and the diminishing size of the rubbish heaps which it produced during each stationary interval, points to a corresponding gradual decrease in the volume of the ice.

Lakes.—We may conveniently consider here the method of the formation of lakes, because a large number of the hollows in which they lie are certainly in some way connected with ice-action, and perhaps have been formed entirely by its agency.

The origin of some lakes is obvious enough. Just as an ornamental sheet of water or reservoir is formed by throwing an embankment across a valley, so the water of some lakes is held back by natural dams, composed of materials different from the rock that forms the bottom and sides of the basin. An old terminal moraine often acts as a dam, the space above, which was once filled with ice, being now occupied partly by water.

In a similar way landslips and streams of lava sometimes block up a valley, and pond back the water of its stream into a lake.

Again, hummocks, such as Eskers, and Sand-dunes, sometimes enclose lakes, the origin of which will be better understood when the student has read in the next section an account of the method of formation of these moundy elevations.

Volcanic craters also are sometimes converted into lakes, when the volcanic activity has become extinct.

Some deposits, such as that known as Glacial Drift, have been thrown down in an irregular manner, with a rough, uneven surface. Water accumulates in the hollows so formed, and gives rise to little lakes.

Another way in which lakes may be produced is by unequal elevation of the earth's surface. This may possibly be the origin of those remarkable lakes in the Jordan valley, which lie far below the present sea-level. There can be no doubt that the long gorge in which the stream flows was cut out by a river, which probably emptied itself into the Gulf of Akabah. Subterranean movements then went on along the basin. The southern end was raised into a barrier, closing the former exit; higher up, the movement gradually changed into one of depression, and along a considerable part of the valley the ground was sunk deep below the sea-level; but the depression was greater at some spots than others, and by this unequal bending down profound hollows were formed along the course of the stream, now occupied by the lakes in question. Till the country has been thoroughly examined geologically, we cannot say that the explanation just given is certainly correct. The folding of the surface into hollows is a possible cause of the origin of lakes that ought not to be entirely overlooked, but at the same time it is doubtful if we can point to a single instance in which it has been conclusively shown that a lake has originated in this manner.

Lakes are occasionally formed in a way somewhat akin to that last described by the dissolving away of beds of soluble materials beneath the surface. This has gone on to a large extent in Cheshire. The New Red Marl, which covers a large part of that county, contains thick lenticular beds of Rock Salt. Percolating water gradually carries these away in solution, and forms great underground cavities, into which the overlying rocks sink down, and so depressions, which are soon filled with water, are formed on the surface. In places where brine is pumped from these beds for the manufacture of salt, the removal goes on more rapidly than under natural conditions and subsidences occur on a large scale.

Lakes are occasionally formed on the alluvial flats of great rivers by changes in the position of the bed of the stream. When the narrow neck of land between the extremities of one of the great winding sweeps of a river is cut through, the entrances to the old channel frequently get choked up, and a portion of the former bed is isolated and converted into a crescent-shaped sheet of water. Sometimes it happens that the whole space between the old and new channels is turned into a lake. The alluvial surfaces are not exactly flat, but usually rise towards the banks of the stream, because it is there that sediment is thrown down most largely; in this way natural embankments are formed along the margins of the river, and when the raised edges of the old and new channels coalesce, and the sunken space between is filled by rain or high floods, a closed sheet of water is produced. Lakes formed by these methods are plentiful along the course of the Mississippi.*

The lakes, however, formed in the ways just described form a very small minority of those which exist. Lakes are most abundant in northern regions, and by far the greater number of these cannot be ranged under any of the above heads. The reader may recollect a picture in *Punch*, where a tourist from a manufacturing district remarks of the Cumberland Lakes, "We call them 'Resevors' in our country." The speech betrayed geological ignorance quite as much as a want of appreciation of the picturesque. These lakes are not bodies of water held back by dams resting on the rock of the country; they lie in hollows which are scooped out in rock itself below the general level of the floor of the valley, and the lip that holds back the water is solid and composed of the same rock as the bottom and the hills on either side. Basins enclosed in this way by an unbroken rim of solid rock all round are called "rock basins," and it is in depressions of this nature that by far the larger number of lakes, in northern latitudes at least, are found to lie.

Fig. 126 is a sketch of a lake, which a little examination proves to lie in a rock basin. Along the sides, and especially on the left-hand margin, the ice-worn surfaces of the hills plunge down steeply beneath the water, and a single glance is enough to assure us that the edges of the hollow are formed of solid rock. The nature of the barrier at the

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* Lyell, Second Visit to the United States, ii. 185, 203, 233.

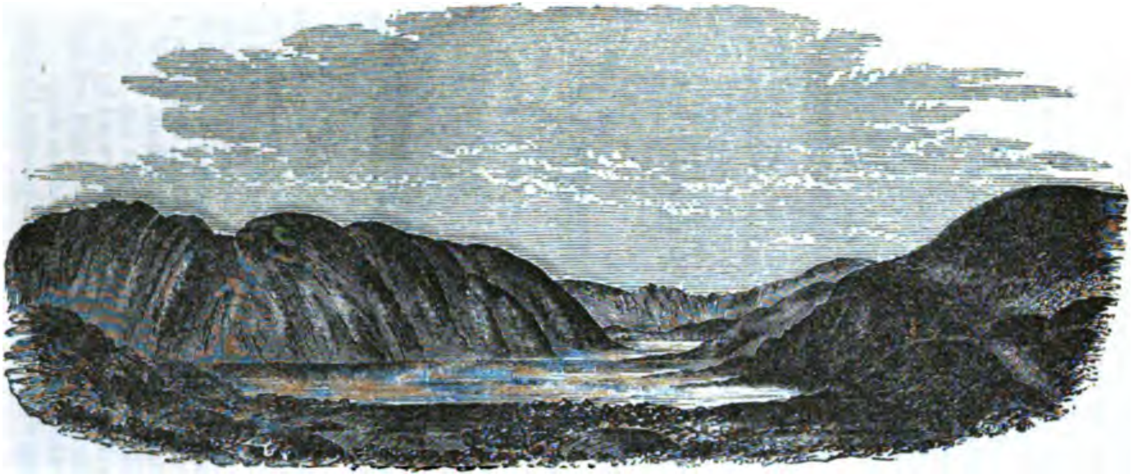

Fig. 126.—Lough Slievesnaght, Co. Donegal, Ireland. A Rock Basin.

lower end is not so obvious at first, for the ground is much obscured by debris from the surrounding hills; but where the stream issues from the lake it has cleared away the loose matter, and we see clearly enough that the water is flowing over a lip of solid rock, and that it is this and not a dam of transported matter that holds back the water.

The reader will notice in the smoothed and rounded outline of the hills, and the moutonnéed bosses that project from the debris in the foreground, signs of former intense glaciation; the surface of the rock also over which the issuing water flows is smoothed and highly polished. We shall see immediately that, wherever rock basins occur, similar proofs of glaciation are present, and that the connection is probably not accidental.

It is evidently not altogether an easy matter to account for the presence of a rock basin. Of the various explanations just given of the origin of lakes none will apply here, unless it be that of unequal sinking of the surface. But a very cursory examination will show that rock basins have not been formed in this way. If they had, the bedding of the rocks beneath ought to be parallel to the bottom of the basin, as in Fig. 127. But such is by no means the case; the beds frequently strike directly across the trend of the lake, dip at all possible angles, and are not unfrequently on end beneath the water, so that their edges must have been worn off to form the dish in which it lies.

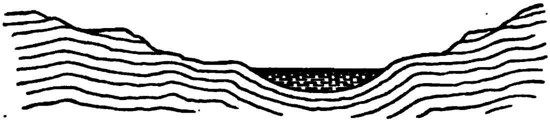

Fig. 127.—Section across a Lake formed by Subsidence.

We must therefore look for something which can scoop out hollows in solid rock, and Professor Ramsay suggested that we should find the tool we want in sheets of ice.

It is evident at first sight that there is no intrinsic impossibility in this hypothesis. Denudation by any fluid agent clearly could not form rock basins, because a running stream, though it might run into a hole, could not run out up-hill at the farther end. But ice, when it has entered a depression, is still driven forward by the pressure of the mass in the rear, and may be forced out again if the slope up which it has to move is not too steep.

Pursuing this line of thought, Professor Ramsay noticed that rock basins are confined to certain countries, where they occur in immense numbers, and that all these countries show signs of former ice-action on a large scale. Scotland, for instance, the Lake district of England, the hilly parts of Ireland, Scandinavia, and North America, were all of them covered with ice at a time geologically recent, and in all of them lakes lying in rock basins are scattered broadcast over the surface, and were once more numerous than at present, because many have been silted up. On the other hand, in those parts of the world which show no signs of former glaciation, lakes are comparatively rare, and many, probably all, of those we meet with do not lie in rock basins.

So suggestive an association led to the idea that rock basins may have been scooped out by ice somewhat in the following manner. When a sheet of ice descends a slope and impinges on the flatter ground at its foot, the extremity, driven down by the pressure of the mass behind, acts like a great gouging tool, and ploughs into the rocks of the plain. The cavity thus commenced is lengthened out as the ice advances, but the force of the thrust will grow less and less as we recede from its source, and also as the glacier moves lower down it melts away, and the thickness, and therefore the pressure due to its weight, gradually decreases. The amount of erosion will thus diminish outwards from the hill-foot, and the hollow formed will gradually shallow in that direction till it comes to nothing. In this way a trough will be worked out with a steep face on the side nearest the source of the ice, and a long slope shelving up gently in the opposite direction. This is found to be very generally the outline of a rock basin. The lake we have already given as an illustration shows it to perfection, as will be seen from Fig. 129, which is a section on a true scale across it and a neighbouring lakelet. The slopes above the head of each lake are ice-worn, not unfrequently to such an extent that they are actual inclined planes, so steep and highly polished as to afford a very insecure foothold when clear of debris; they plunge down at once into the water without the least

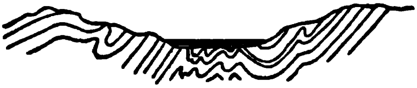

Fig. 128.—Section across a Rock Basin.

change of inclination, the submerged portion being a direct continuation of that above the level of the lake. At the lower ends rock surfaces, equally well smoothed, rise at a low angle from beneath the water and slope up gently till the next abrupt descent begins.

There can be no question that the basins have been filled with a mass of moving ice, and we can readily realise how they may have been formed altogether by such an agent. A glacier, cascading as it were down a steep face, was driven forcibly against the flatter ground at the foot, and ate out a hole which was the beginning of the basin. A hollow once started, the constant wearing of the ice-flow would enlarge and deepen it, but it is easy to see that the slope of the bottom would be smaller at the lower than at the upper end; down the one the ice slides with gravity in its favour, while it has to move up the other against the action of gravity; when it enters the hole, therefore, its erosive power is greater than when it is leaving, so that in the one case a larger amount of material is removed and a steep face is produced, in the other a more gentle slope is formed. In fact, the ice having got into the hole must get out of it, for the pressure from behind will not allow it to stand still. But the only way of getting out is to wear down the rock that stands in its way to a slope gentle enough to allow of the mass sliding up it.

Exactly similar results will follow wherever a great sheet of ice flows over an uneven surface. We only want a depression to begin with. Wherever there is a little hollow, the ice will go down into it, wear it deeper, and give it the same sort of shape as the basins just described. Not that rock basins will always exactly conform to this pattern. The relative hardness of the rocks of their floor will modify the result, greater erosion and therefore greater depth being produced where the ice crosses beds relatively soft. The thickness of the ice will also have an important effect; when it has once been started at its work, the thicker the sheet the greater will be the weight driving it down, and the greater the depth to which it will penetrate. Rock basins will therefore be most likely to be formed, all other things being equal, beneath those parts of an ice-sheet where it is thickest.

It is important for the full understanding of the theory of the ice origin of rock basins that the student should clearly realise how very shallow in comparison with their length these hollows are. Owing to the very general practice of using a scale for heights and depths larger than that employed for horizontal distances, most illustrations convey a very false idea of the shape of rock basins. The section of Lough Maam in Fig. 129, a section of the Lake of Geneva, given in Professor Ramsay's paper quoted below, or the section of Loch Lomond, facing p. 518 of Mr. James Geikie's "Great Ice Age," all of which are drawn to a true scale and therefore do not exaggerate the slopes, show clearly that these depressions, large as their absolute depth seems, are, when their relative dimensions are taken into account, only shallow pans, and that the inclination of their beds is by no means so great as that of many surfaces up which ice-sheets have certainly flowed.

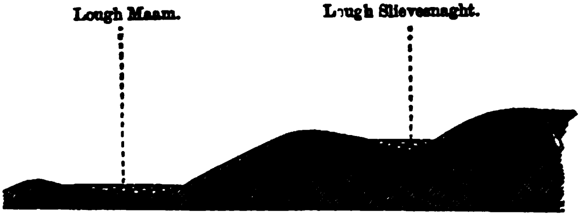

Fig. 129.—Section along Lough Maam and Lough Slievesnaght, two Rock Basins, Co. Donegal, Ireland.

The above explanation of the origin of rock basins was at first violently opposed. It has, however, gradually grown in favour, and some eminent geologists, who at one time would not hear of it, have given in their adherence to the views of its author. It may safely be said to be a reasonable and consistent explanation, and the invariable association of glaciation with rock basins is a strong argument in favour of the two standing to one another in the relation of cause and effect, even if we have not yet hit upon the exact nature of the mechanism by which ice has been able to scoop out the hollows.*

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* The reader who wishes to go more fully into the subject may turn to Ramsay, Quart. Journ. Geol. Soc., xviii. 189; Phil. Mag., Oct. 1864, and April, 1865; A. Geikie, Transacts. Geol. Soc. of Glasgow, i. 86, and iii. 180; Belt, Quart. Journ. Geol. Soc. xx. 463; Haast, ibid., xxi. 130; Gastaldi, ibid., xxix. 396; Ward, ibid., xxv. 96, xxxi. 152; J. Geikie, The Great Ice Age, xxi.

SECTION V.—SURFACES NOT WHOLLY DUE TO DENUDATION.

So far we have been dealing with ordinary hills and valleys—what we may call everyday features—and we have seen that not only is denudation quite competent to produce these inequalities, but that we know of no other agent among existing forces that could have formed them. Valleys we have learned to look upon as troughs or trenches dug out by denudation, just as much as a ditch is dug out with a spade, while hills are the remnants which denudation has spared. There are, however, certain reliefs of the earth's surface, in the formation of which denudation has played only a subordinate part, and to these we will now turn our attention.

The most important of the features that come under this head are Mountain Chains; next in order we may put Volcanic Cones; and then we shall have to notice the minor instances of Eskers, Moraines, Sand-dunes, and Alluvial Flats. In the case of all but the last we shall find that, though their main outlines have been determined by some cause other than denudation, they have by no means been unaffected by that all-present agent, and that all the lesser details of their surface-form are due to its action.

Mountain Chains.—The word mountain in its popular acceptation can be scarcely said to carry with it any very definite meaning. It is used vaguely for a very high or otherwise noteworthy hill, but the limit above which a hill must rise before it can be entitled to be called a mountain is purely arbitrary, and depends largely on its surroundings. The Rigi, for instance, is so dwarfed by the neighbouring Alpine peaks, that it is reckoned no more than a subordinate summit; if it were transported to the flats of Holland, it would be there looked upon as a conspicuous mountain.

But it is possible to frame a definition, though perhaps not a very rigid one, of what is meant by a mountain chain. The one great leading feature which distinguishes mountain chains from the hills and ridges we have hitherto been dealing with we shall find in the end to be this. They are not blocks of rock that stick up because the matter that once surrounded them has been removed by denudation; *they owe their superior elevation to the fact that the rocks of which they are composed have been squeezed and ridged up to a greater height than the rocks of the country on either side.*

But this is not a truth that can be learned by direct observation; it is rather a conclusion we arrive at only after having gone through a somewhat complex train of reasoning; it is not therefore very well suited to form the basis of a definition. But if all the regions that have undergone this squeezing-up process are found to agree in possessing certain simple and easily recognisable external characters, and if these characters are not found anywhere except in such regions, we shall have in these peculiarities a means by which the eye alone can decide whether any given tract of lofty ground is, or is not, entitled to be called a mountain chain.

Now there are two distinguishing features which most, if not all, mountain chains present.

1st. Their breadth is small compared with their length.

2nd. They rise sharply, and are marked off clearly, from the country on either side.

It is by the first of these tests that we distinguish between a true mountain range and a mere lofty plateau. The former consists of a long narrow ridge, or a succession of ridges running rudely parallel to each other, along the crests of which *projecting peaks are perched in lines approximately rectilinear*. A plateau, or table-land, is a broad expanse of elevated ground of a tolerably uniform height all over, and *any points that rise prominently above its level are liable to be dotted about without order or arrangement.*

This chain-like structure may always be recognised if we take a broad view of any great mountain range, though here and there it may be difficult of detection, or may be for a while lost altogether. This will be the case at those great knots of mountains which are formed where two or more ranges meet or cross one another; but such exceptions are of the nature of local accidents, and do not prevent us from realising the general character of the ridges as a whole, any more than the fact that a long street opens out every here and there into broad squares, prevents our seeing that, on the whole, it is a street and not a square.

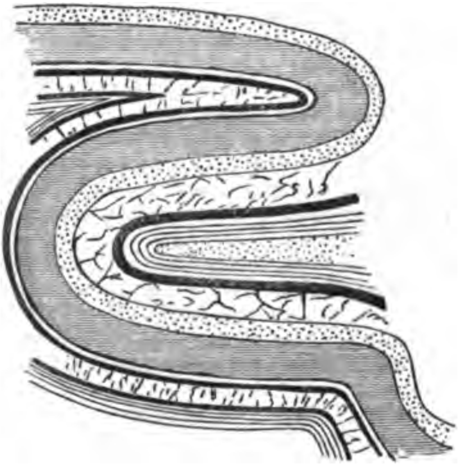
The second feature will be found to be present to a far greater or less extent in all great mountain ranges. It is true that the main central chain is usually flanked by lower parallel ridges, and that these lessen in some measure the abruptness of the transition from the high lands to the plains, and make it difficult to say exactly where one ends and the other begins; but for all this the eye seldom fails to recognise on a general view the existence of a change in feature more or less sudden, even though it may be hardly possible to lay one's finger on the actual spot where it occurs.

The reader will perhaps form a good idea of the broad structure and general character of a mountain chain in this way. Let him take a number of long, squat, triangular prisms, of different sizes, and lay them, with their broad faces downwards, parallel to one another on a table, the highest in the middle, the smallest outside, and the rest ranged between in the order of their size; then let him cut and hack the upper edges till their outline becomes jagged and serrated. The group will then form a very fair representation of a mountain chain composed of a number of parallel ridges, increasing in height towards the centre, and with prominent peaks ranged along their crests; and the way in which the group is clearly marked off from the flat of the table will enable him to realise how a mountain chain rises boldly and sharply out of the country on either side of it.

The definition just given will exclude from the class of mountain chains many tracts of lofty country usually spoken of as mountainous. For instance, it will not allow of the existence of mountain ranges in the Highlands of Scotland. If we were to look down on that country from a balloon, we should see nothing corresponding to our table and array of prisms. On the contrary, it would appear to be a great table-land, not perfectly flat, but with a surface slightly undulating like that of a sea roughened by the wind; valleys would be seen to cut across it, but they would look like trenches, and would scarcely interfere with the apparent general evenness of the surface. And if we checked this first impression by the aid of a raised map of the district, we should find that our eyes had not deceived us. A sheet of paper laid horizontally on such a map will touch, or very nearly touch, the tops of almost all the hills; here and there a hole may have to be made to allow a projecting point to come through, but these are few in number, none of them rise much above the average level of the surrounding summits, and most of them occur at haphazard and with no tendency to a linear arrangement.

On the other hand, if we turn to Italy, we shall realise the contrast between a lofty table-land, like that of Scotland, and a true mountain chain; for the Apennines, in spite of their moderate height, are clearly entitled to that rank. They form a range decidedly long and narrow, and they are flanked on both sides by ground markedly inferior to them in elevation.

The two distinguishing features on which we have been commenting, though they are useful as enabling us to recognise mountain chains, throw no light on the mode of their formation. We now pass on to a fact which has a most important bearing in this direction. All hill ranges which present these features are found to agree in possessing another peculiarity. *The strata of which they are composed are always found to have been violently disturbed.* The most striking form of distortion is crumpling on an extensive scale, by which the beds have been folded into curves of enormous radius, and puckered up into the most complicated contortions; in many cases this has gone so far as to bend over the rocks in the manner shown in Fig. 130, and give rise to perfect and repeated inversion.



F . 130.—INVERSION OF MOUNTAIN STRATA BY INTENSE FOLDIN

Instances of this kind have already been given, and it has been pointed out how completely mountain sections may mislead us as to the true order of the beds, when parts of the folds have been removed by denudation. Faulting on a large scale is also very generally met with among the disturbed strata of mountain chains, and it is said that the faults are frequently reversed. The axes of the folds and the faults are in a general way parallel to the trend of the range.

It must not be supposed that the distinction between mountain chains and plateaus can be always rigidly maintained; there are elevated tracts which are somewhat intermediate between the two, and about which it is not easy to say to which class they ought to be referred. The strata of table-lands are sometimes folded and contorted very much in the same manner and nearly to the same extent as those of mountain chains, and show locally intense crumpling and inversion. But in the one case the plication has been widespread, and the resulting contortion is consequently on the whole less violent; in the other it has been localised and concentrated along certain lines, whereby the effects have been rendered more pronounced and confined to a comparatively narrow belt.

The reader will now, it is hoped, have arrived at a clear notion of what it is that constitutes a mountain chain. It is a long narrow range of very lofty ground, sharply marked off from the country on each side, and the strata of which it is composed are violently disturbed, as if they had been squeezed together forcibly in a direction at right angles to the axis of the chain.

These being the facts, to what conclusion do they lead us as to the method of formation of mountain chains?

We have already seen reason to believe that the process which gave rise to areas of dry land consisted in a folding of the earth's crust into arches and troughs, that continents are in a broad sense the denuded backs of arches, and that oceanic depressions have had their rise in troughs. Now we have only to suppose this same folding process to act with intense energy along certain lines, and we have the machinery competent to produce a mountain chain. A long narrow ridge would be gradually raised above the general surface, and if elevation went on faster than denudation could wear down the protuberance, a range of high ground rising sharply from the country on either side would be permanently established. At the same time the thrust, which squeezed up the range, would contort and crumple the strata into folds ranging parallel to its length. It must not be supposed that all the work was done at the same time; the process was repeated probably over and over again along the same general line, and thus at length the great mountain ranges were brought to their present elevation. On this view all the great leading reliefs of the earth's surface are the result of a kind of shrivelling, and mountains are the more prominent wrinkles.

To this theory of mountain-building no serious objection has yet been urged, and it certainly looks as if it contained the elements of a true explanation, even if it be not the full explanation itself. There are, however, certain difficulties in the way of accepting the accompanying explanation of the origin of continents and oceanic troughs; these have been already hinted at, and will be more fully treated of in the next chapter.

There are two more facts which support the conclusion that the elevation of mountain chains was the work of lateral thrust. The one is the presence of cleavage, the planes of which range parallel to the axis of the chain; this is a proof that the rocks have been compressed in a direction at right angles to that line. The other fact is that mountain chains usually show a central core or axis of Granite or some allied rock, which shades off insensibly on either side into Gneiss, Mica Schist, and other highly metamorphic forms, while from these last a gradual passage can be traced into unaltered beds (see Fig. 138). In other words, since the Granite probably marks only the extreme stage of metamorphism, the interior of a mountain chain consists of intensely metamorphosed rocks, and the alteration grows less and less as we recede from the axis till it disappears altogether. Now the pressure required by our theory may well have given rise to heat sufficient to produce, in conjunction with other agents, this metamorphism.

The bulk of a mountain chain, then, must be supposed to have been raised to its present position by the violent crumpling up of a narrow strip of the earth's crust. But this was only the first step in the process of its formation. While this was going on denudation was not idle, and it continued to work when the elevation was completed. As the ridge was raised higher, it became more and more exposed to the action of the elements, and subaërial denuding forces were enabled to act upon it with more and more telling effect. By them the huge uncouth mass was gradually worked into its present shape, and carved out into an assemblage of bristling peaks, craggy precipices, ragged gorges, and open valleys.

It may be asked whether it is necessary to call in the aid of special machinery for the production of mountain chains, and why they cannot be looked upon, like other hills, as simply the remnants of denudation. There are two main reasons why we must seek an explanation of the origin of mountain chains different from that which sufficed for ordinary elevations.

In the first place, what we may call the isolation of mountain chains is a ground for calling in some special agency for their production. Where intense contortion, cleavage, and metamorphism are manifested only along a certain band, there is good reason for thinking that the forces which gave rise to these phenomena were confined to that band, or at least acted with unusual intensity within it. Secondly, in order to get a mountain chain by denudation alone, an amount of rock, far greater than we have any reason to believe denudation can have removed, must have been carried away.

We have seen that possibly the ultimate source of the elevating force was in all cases the same; that where it extended over a broad area, an embryo continent was produced; but where it was limited to a comparatively narrow belt, its intensity was thereby increased, and the rudiments of a mountain-chain were the result. In either case it was certainly denudation that gave the finishing touches, and carved out all the lesser details of the outline.

Volcanic Cones.—Volcanic cones, the reader will recollect, are mounds of fragments of rock, which were shot out of a hole in the ground, and piled up in a heap round it, with layers of lava poured from time to time over the pile in a semi-fluid state out of the same orifice. Neither denudation nor elevation had anything to do with their original formation, but the former agent of course, as time goes on, modifies their shape; by the washing down of their friable materials their conical abruptness is diminished, and gullies and gorges are scored down their flanks.

Eskers.—Among the most remarkable of the minor features of hilly districts in northern latitudes are certain long, winding ridges and hummocky mounds of gravel and sand, which go by the name of Kames in Scotland, and Eskers in Ireland. They rise boldly and sharply with steep slopes, to heights of occasionally as much as 100 feet and sometimes more, from the ground on which they stand, and the singularity of their appearance has attracted the attention of others beside geologists. Fairy legends still hover around them; they are pointed out as the ropes of sand in the manufacture of which an enchanter strove to keep a restless demon out of mischief; and they were utilised as natural earthworks in the days of early warfare.

To account for the origin of these singular hillocks, numerous theories have been propounded; there can be little doubt, however, that they have not all been produced in the same way.

Some so-called eskers are certainly nothing but mounds, which have been carved by denudation out of a thick sheet of gravel; these present no peculiarity which entitles to notice in the present section.

But there are others to which this explanation will not apply, and which undoubtedly owe their shape in a large measure to the manner in which their materials have been heaped up.

Several facts lead us to this conclusion. It not unfrequently happens that the long ridges run together, and enclose oval-shaped hollows *without an outlet*, which are sometimes still occupied by tarns, and sometimes by peaty or alluvial deposits formed by the silting up of lakes that once lay in them. It is evident that these depressions could not have been cut out of a sheet of gravel by rain or river action, because there is no road by which a stream of water could escape from them; and the only way we can account for their occurrence is by supposing that the gravel was piled up in heaps round the central hollow, so as to enclose it completely on all sides.

This conclusion is further strengthened by the internal structure of the kames. When cut across, they show a section like that in Fig. 131. The gravel is very distinctly though irregularly bedded, and the beds arch over, so that, in a general way, the direction and amount of the dip is about the same as the slopes of the surface of the ridge. This is just the structure that would be produced if the materials had been heaped up by currents coming alternately from opposite quarters. Such conditions exist where a river with fall enough to enable it to carry down

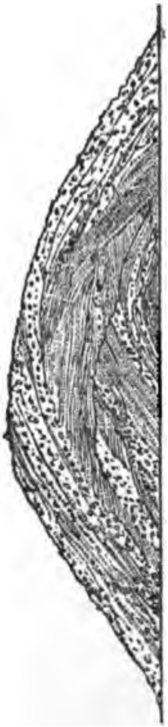


Fig. 131.

gravel enters a tidal sea. The greater part of the heavy material is let fall near the mouth of the river and forms a "bar." At low water there is nothing to check the force of the stream, and it rolls the gravel up the inner face of the bar and arranges it in layers dipping towards the land; as the tide rises the river is pounded back, and the incoming waves roll pebbles up the outer face of the bar, spreading them out in beds which dip towards the sea.

At very many spots where eskers occur, exactly such conditions as these would be produced if the land were submerged. Eskers are extremely common, for instance, where large mountain valleys open out into flatter country. Supposing the sea to encroach as far as the mouths of the valleys, the load of debris brought down by the mountain torrents would be tossed about alternately by the stream and the incoming tide, and arranged in mounds and ridges.

An excellent instance of eskers lying in such a situation is found in the lower part of Ennerdale, and is illustrated by Fig. 132. The sketch is taken just where the hills of the Lake country begin to rise from the plain of West Cumberland. The long, narrow mountain-valley is seen stretching away in the distance; the two moundy hills in the foreground with trees on them, are eskers planted just where the valley opens out on to the flat country; they form part of a group which runs across the mouth of the valley, and extends far out into the plain.

Another favourite locality for eskers is a valley, which submergence would convert into a narrow strait connecting opposite seas. Along such a passage tides coming in opposite directions race furiously, and, where they meet, the materials swept along by the currents are piled up in mounds and ridges having the outline and structure of eskers. Some fine groups of eskers are perched on plateaus; in such a case we find that a certain submergence would convert the plateau into a low spit of land, over which the tides would wash at high water from opposite quarters.

One or other of the explanations just given will account for the formation of a large number of these singular hummocks, but not for all. We occasionally meet with long snake-like ridges, winding over the country with considerable disregard to the inequalities of the surface, and it is by no means easy to say exactly how these were formed. In Scandinavia again, long ridges of gravel and sand, known as Åsar, are plentiful; they can sometimes be

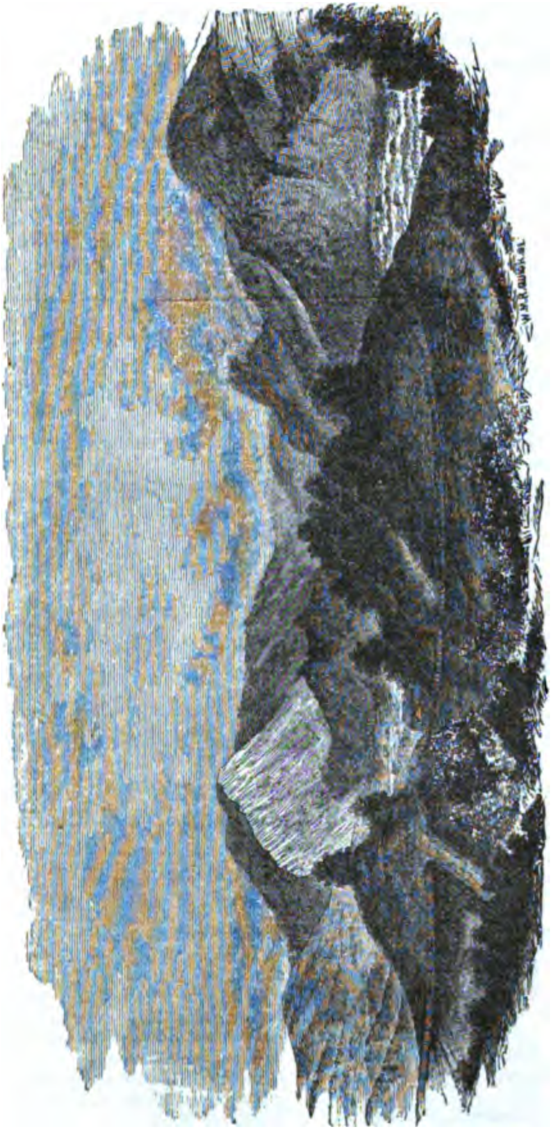


Fig. 132.—Eskers at the Mouth of Ennerdale.

traced for more than a hundred English miles, and their origin has not yet been satisfactorily made out.*

Moraines.—Among the minor reliefs not due to denudation we may reckon Glacier Moraines. In outward form they are often very like eskers, and the two have not unfrequently been mistaken for one another. In section, however, it is always possible to distinguish between them. The gravel of an esker is usually well bedded; a moraine consists of angular blocks of all sizes and shapes, jumbled together without order or arrangement, and with no regard to size or weight. The moraines of large glaciers form hills of considerable size: those of the Dora Baltea, opposite the mouth of the valley of Aosta, rise from the plains of Piedmont to heights of 1,500, and in one place of nearly 2,000 feet, and have a frontage of at least fifty miles; the lateral Moraines stretch along the valley in ridges equally conspicuous.

Sand Dunes.—Somewhat allied to eskers are the mounds of sand swept off the shore by winds and piled up inland in hillocks. They often reach a considerable height and assume wild fantastic forms; the slope of the inland side is much steeper than that of the side which faces the sea; in section the successive layers by which they were formed can often be traced. They are never permanent, but shift their position and change their shape with every gale.† Though most commonly found near the shore they are not confined to that locality, but are formed far inland if a supply of fine dry sand is present. Thus the sand furnished by the weathering of the Bunter Sandstone of the centre of England is sometimes heaped up into small dunes.

Lakes enclosed by heaped-up Mounds.—The different kinds of mound-like elevations just described, which have been formed by the heaping up of their materials, are frequently so arranged as completely to enclose a hollow, and when this becomes filled with water a tarn or lake is produced.

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* See A. Geikie on the Glacial Drift of Scotland, p. 112; J. Geikie, The Great Ice Age, p. 385: and Geol. Mag., ix. 307: some very happy suggestions in a paper of Prof. Jamieson's, Quart. Journ. Geol. Soc., xxx. 317: Kinahan, Explanation of Sheets 115 and 116 of the Geol. Survey Map of Ireland, pp. 13 and 30; Dublin Quart. Journ. Science, iv. 109, vi. 249; Dublin Geol. Soc. Journ. x.; Journ. Royal Geol. Soc. of Ireland, vol. i. pt. 3; Geol. Mag., 2nd ser., ii. 86.: Rev. M. H. Close, Journ. Royal Geol. Soc., of Ireland, vol. i. pt. 3.

†For an account of the extensive Sand Dunes of Les Landes, which are among the largest known, see Elie de Beaumont, Leçons de Géologique pratique; Brémontier Mémoire sur les Dunes; E. Reclus, Le Littoral de la France; Delesso, Lithologie du Fond des Mers.

Alluvial Flats.—When a tract of ground not permanently under water becomes submerged during floods, the materials held in suspension are thrown down as the water comes to rest. Deposits formed in this way are called *Alluvial.* If the floods recur frequently, any inequalities which denudation may produce in the interval between two submergences, are filled up by the deposit of sediment, and a smooth even surface is constantly maintained; hence the surface of alluvial deposits is usually flat.

River Flats.—The valley of a river flowing through easily denuded rocks generally has, over that part of its course where the fall is too small to allow of the deepening of the channel, a broad flat bottom of rich meadow land, over which the stream winds in broad curves. From this on either side the ground rises in steep banks or cliffs. The flat is periodically flooded, and the matter held in suspension falls down as the force of the flood abates, and is spread out in broad smooth layers.

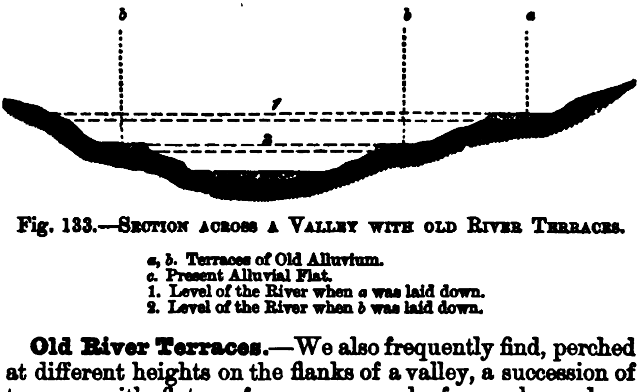

Fig. 133.—SECTION ACROSS A VALLEY WITH OLD RIVER TERRACES.

a, b. Terraces of Old Alluvium.
c. Present Alluvial Flat.
1. Level of the River when *a* was laid down.
2. Level of the River when *b* was laid down.

Old River Terraces.—We also frequently find, perched at different heights on the flanks of a valley, a succession of terraces with flat surfaces, composed of gravel, sand, or silt, similar to that of the alluvial bottom. These are the remnants of old alluvial flats formed by the river when it flowed at higher levels than now. Fig. 133 is a section across such a valley, showing two such terraces. The dotted line (1) marks what was at one time the bottom of the valley. The river flowed at this level, with a fall not sufficient to enable it to cut down its bed, long enough to enable it to spread out a sheet of alluvium. Afterwards, owing to a change in physical geography, the fall or volume of the river increased; it began to cut down its channel, and the valley was deepened. During this process the whole of the alluvial sheet was carried away except the bit at *a*. The deepening of the valley went on till it was cut down to the level (2), when the fall was so far decreased that erosion ceased, and a second alluvial flat was produced. Then the deepening process began again, a great part of the second alluvial deposit was swept off, but two patches (*b b*) remain at corresponding levels on either side of the valley to mark its position. When the valley had been eaten out to its present depth, the stream again began to form deposits on each side, and produced the present flat (*c*).

Many river terraces have been formed in the manner just described, but probably not all. For instance, a very ingenious explanation of the formation of gravel terraces by the aid of glaciers has been suggested by Professor Jamieson in the paper quoted a little way back (Quart. Journ. Geol. Soc. of London, xxx. 333).

Sea-beaches.—We have seen that the action of the sea tends to wear down whatever stands in its way to a uniform level. By this means, if the land remain long enough at the same level, a notch or shelf is cut around the coast, and upon the terrace so formed the tides spread out sand and shingle.

Raised Beaches.—These sea-beaches correspond among marine deposits to the alluvial flats of rivers; and just as a river valley is sometimes edged with old alluvial terraces, so we occasionally find terraces of sea-sand and shingle, fringing the coast at various heights above the present sea-level, which were formed when the land stood lower than at present. Fig. 134 illustrates such a case. *A* is the present beach bounded on the landward side by a ridge (*B*) of shingle thrown up by the waves. Above this there is an old beach (*a*) and a shingle ridge (*b*), corresponding in every respect to *A* and *B*, and evidently formed when the land stood so much lower that the tides ran up as far as *b*.

These old marine terraces go by the name of Raised Beaches; they are frequently bounded towards the land by lines of bluffs, in which it is easy to recognise former sea-cliffs; the caves worn in them by the action of the waves, and sometimes even the marine shells that lived on their face, often remain long after the sea has retired.

Surfaces of Deltas.—When a tract of low land has been formed by the accumulation of sediment at the mouth of a river, fresh-water or marine alluvium is spread over it during floods or high tides, and it acquirés an even surface. In this way the whole of the Netherlands has been formed out of mud brought down by the Rhine.

Silted-up Lakes.—Where a lake has been filled up by the deposition of sediment, a flat resembling the alluvial plains of rivers is produced.

In all these cases of alluvial surfaces their flatness is the result, not of denudation, but of the slow and regular deposition of sediment in horizontal beds. As they are for the most part low-lying, they occupy positions where the action of denudation is feeble, and they therefore retain for a long time their original evenness of surface.

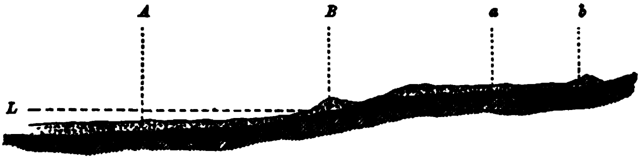

Fig. 134.—Section of Modern and Old Sea-beach.

A. Modern Beach. B. Modern Shingle Ridge.
a. Ancient ditto. b. Ancient ditto.
L. Present High Tide Level.

Prairies and Deserts.—It seems likely that the wide, rolling, dry prairies of North America have originated in the filling up of a great sheet of water which once extended over parts of Iowa, Illinois, Indiana, and Michigan, and of which the present North American lakes are the dwindled remnants.*

It may be also that deserts, such as the Sahara and those in the interior of Australia, are old sea-bottoms but little modified by denudation,

Summary.—When we come to sum up the results of this chapter, we find that, with a very few unimportant exceptions, the dry land has everywhere a carved and sculptured surface, and that the tool which gave it its present shape was water, liquid or solid.

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* On the Origin of the Prairies of the Valley of the Mississippi, Prof. Alex. Winchell, Silliman's Journ., 2nd ser., xxxviii. 332, 444.

In the majority of cases, the contours and inequalities of the ground are due to this cause alone; hills exist, not because the materials of which they are composed have been pushed up higher than the surrounding country, but because, while denudation carried away some parts, other parts were better able to hold out against its wearing action and were left standing up. Valleys have not been produced by a bending down or fissuring of the earth's crust, but are trenches eaten out by running water or moving ice.

The sea and subaërial denuding forces had each a distinct share in the work. As continuous gentle elevation raised the sea-bottom into the air, the waves pared it down to an even surface, known as a Plain of Marine Denudation, and subaërial agents carved this out into hills and valleys. The action of the one may be compared to the labour of the quarryman, who furnishes a rough-hewn slab; the work of the others resembles that of a sculptor, who carves out on the surface of the marble a subject in relief.

In the case of great mountain chains however and the broad valleys that lie between them, the elevatory forces have played a more prominent part in determining the shape of the surface. A long narrow zone of the earth's crust was ridged up faster than denudation could wear it away, or under circumstances where denudation could not act, and thus the main shape and direction of the range was established. Thus much must be assigned to elevation, but all the lesser details are the work of denudation, which cut out the peaks that crown and the gorges that traverse the ridges.

In some cases, then, elevation has had a leading share in determining the reliefs of the earth's surface, and water has given the finishing touches; in the majority of cases the inequalities, great and small alike, have been wholly the result of denudation.

The chief exceptions to this sweeping statement are the cones heaped up by volcanic discharges; the mounds and ridges of sand and gravel piled up by waves and wind; moraines; and the flats formed by the deposition of alluvial sediment and by the silting up of lakes.

Of the abundant literature on the subject of the present chapter the following may be specially commended to the reader's notice:—

Hutton's Theory of the Earth, and *Playfair's* Illustrations of the Huttonian Theory.

Scrope.—The Geology and Extinct Volcanoes of Central France, chap. ix.

Ramsay.—On the Denudation of South Wales and the adjacent Counties of England. Memoirs of the Geological Survey of Great Britain, i. 297. The Physical Geology and Geography of Great Britain.

The Old Glaciers of Switzerland and North Wales.

J. B. Jukes.—On the Mode of Formation of some of the River Valleys of the South of Ireland. Quart. Journ. Geol. Soc., xviii. 378.

A. Geikie.—The Scenery of Scotland viewed in connection with its Physical Geology.

On the Phenomena of the Glacial Drift of Scotland. Transacts. Geol. Soc. of Glasgow, vol. i. part 2.

Earth Sculpture. Nature, ix. 50. Transacts. Edinburgh Geol. Soc., ii. 248.

W. Whitaker.—Subaërial Denudation. Geol. Mag., iv. 327, 447, 483.

C. Le Neve Foster and *W. Topley.*—On the Superficial Deposits of the Valley of the Medway, with Remarks on the Denudation of Valleys. Quart. Journ. Geol. Soc., xxi. 443.

W. Topley.—Notes on the Physical Geography of East Yorkshire. Geol. Mag., iii. 435.

J. Geikie.—The Great Ice Age, chap. xxi., Note D.

Prof. F. V. Hayden.—United States Geological Survey of the Territories. Profiles, Sections, and other illustrations designed to accompany the final report of the Chief Geologist of the Survey. New York, Julius Bren, 1872. (Contains admirable instances of escarpments, dip-slopes, tabular outliers, and other features resulting from denudation.)

Sun Pictures of the Rocky Mountains.

The reader will do well to compare with the theory of surface-sculpture upheld in the preceding memoirs, chapter xix. of the late Prof. Phillips's Geology of the Valley of the Thames. Elegant and ingenious as is the explanation there put forward, there is about it an unsatisfactory vagueness and want of definition, which contrasts strongly with the sharp precision and logical coherence of the views on the subject of which a sketch has been attempted in the preceding pages, and which are steadily gaining ground among modern geologists.

CHAPTER XI.

ORIGINAL FLUIDITY AND PRESENT CONDITION OF THE INTERIOR OF THE EARTH. CAUSE OF UPHEAVAL AND CONTORTION. ORIGIN OF THE HEAT REQUIRED FOR VOLCANIC ENERGY AND METAMORPHISM. REMARKS ON SPECULATIVE GEOLOGY.

> Sit mihi fas
> Pandere res alta terra et caligine mersas.
> VIRGIL.

SECTION I.—THE PRESENT PHYSICAL CONDITION OF THE EARTH.

IT was pointed out in the opening chapter that the geologist's first business was to make himself acquainted with those portions of the earth which he could actually observe, or the nature of which observations made on the surface would enable him to infer with very trifling risk of error; and that, until he had mastered this branch of the subject, he would not be in a position to speculate on the character of the inaccessible interior. The time has now come when we may enter upon this fascinating but, in the present state of our knowledge, somewhat unsatisfactory theme.

The subject is not one of barren curiosity. Till we do know what is going on far down under our feet, we can only very imperfectly explain several things that are happening or are now visible at the surface. We cannot say, for instance, where lies the source of volcanic energy, or what is the force that has given rise to folding, contortion, and faulting. When we reflect on the great importance of a thorough knowledge of faults to the miner, we see that even the somewhat abstruse speculations in which we are about to indulge are not without a practical bearing.

It is evident that we can learn nothing by direct observation about the nature of the earth's interior. As in all those cases where we have to reason about matters which are beyond the grasp of our senses, we must begin with an hypothesis, which may be suggested to us by some facts of observation, or may be purely the outcome of our own mental ingenuity. We then ascertain by deductive reasoning what results would follow if our hypothesis were true. Finally, we compare the consequences that follow from the hypothesis with the observed facts; and the probability that our hypothesis is correct rises in proportion as the points of agreement between the two become more numerous and exact.

Now in the case before us the main facts we can learn from observation, which are of use in checking and estimating the probability of the truth of any hypothesis that may occur to us, are these—that the earth is a spheroid of revolution very nearly; that its mean density is about double the average density of the surface rocks; and that, as far as we have been able to penetrate, it grows steadily hotter as we go down, and must therefore be constantly losing heat.

Any speculations we may indulge in about the deeply seated regions of the earth must be consistent with these facts of observation; but the facts do not of themselves help us much to an hypothesis about the nature of the interior and the process by which its present condition was arrived at.

Some such hypothesis we must have, and it appears that we must either trust entirely to our own ingenuity to invent it, or look beyond the earth for the facts that are to suggest it.

Now observation of cosmical phenomena has suggested a theory of the development of the solar system known as the Nebular Hypothesis, which, if it can be securely established, will aid us materially in our present inquiry, for it will tell us what was the state of the earth's interior at a very remote period, and what changes it has been passing through since, and so will enable us to make very probable conjectures as to the condition it has by this time arrived at.

This hypothesis was originally sketched out by Kant, and was afterwards more fully developed by Laplace. The substance of it is as follows.

There are in the heavens faintly luminous cloudy masses known as nebulæ, and the spectroscope has lately revealed to us the fact that some of these are bodies of glowing hot gas, and the appearance of some of them is such as would be produced by rotation round an axis. As the heat escapes from these by radiation into space, they must contract; whenever from time to time the shrinking has gone so far that the central attraction is no longer able to overcome the tendency of the outside portion to fly off, a ring is separated which afterwards collects together into a ball. By a continuation of this process the nebula is at last broken up into a number of balls, all of which revolve round the centre of the original mass and rotate on their axes in the same direction, and a central globe, which retains its heat after the balls have parted with a large portion of theirs. In a word, the nebula is in this way transformed into a group of planets revolving round a central sun. The theory which supposes the solar system to have originated in the manner just sketched out, accounts so satisfactorily for many of the main characteristics of the planetary system, that there is a very strong probability in favour of its being true. But for details on this head the reader must turn to works on astronomy; we have to do with the theory here only so far as it concerns the earth. According to it, our globe was originally an intensely heated, rotating mass of gas, and has assumed its present form by gradual cooling.

Our task, then, will be first to lay before the reader all the facts about the constitution of the earth which can be gathered from observations made at or near the surface; secondly, to see how far these facts fit in with and confirm the hypothesis of the nebular origin of the earth; and, thirdly, assuming that hypothesis to be true, and that the earth was once fluid, to inquire if we can form any estimate of the state to which the interior must by this time have been brought, whether any portion still remains fluid, or whether solidification has extended from surface to centre.

Shape of the Earth.—In order to get a proper notion of what is meant by the shape of the earth, it is necessary clearly to realise that even the very largest inequalities of its surface, the loftiest mountains and the deepest oceanic depressions, are very small indeed compared with the distance from the centre to the surface, and may be altogether neglected when we look at our globe as a whole. So small are they, that, if we could take a journey into space and view the earth from a moderate distance, its outline would look as even and regular as that which the moon presents to us.

In this broad sense it is well known that the earth may be readily proved to be globular in shape, and that more accurate investigations show it to be not an exact sphere, but to be flattened like an orange. The question of the determination of the exact figure of the earth has engaged the attention of many mathematicians, and they have shown that the form which agrees best with the observed measurements is that of a solid generated by the revolution of a half ellipse, *A B b*, Fig. 135, about its shortest diameter, *B b*. The name given to such a solid is an oblate spheroid; *B* and *b* are the poles, *B b* the polar axis, the circle described by *A* the equator; and if *C* be the middle point of *B b*, *A C* is the equatorial radius or axis. In the case of the earth *A C* is a little short of four thousand miles, *B C* between thirteen and fourteen miles less.*

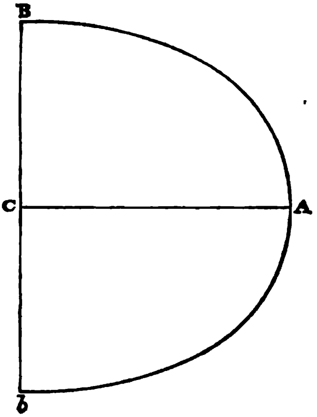

Fig. 135.

For an account of the methods used to determine the figure of the earth the reader may refer to Lockyer's Elementary Lessons in Astronomy, chap. viii.; Airy's Ipswich Lectures, pp. 36—51; Encyclopædia Metropolitana, Art. "Figure of the Earth;" Baily, Astronom. Soc. Memoirs, vol. viii.; Sir H. James, Phil. Trans., 1856 (vol. cxlvi.), p. 607; Comparisons of Standards of Length, Ordnance Survey of Great Britain, Appendix; Archd. Pratt, a Treatise on the Figure of the Earth, 4th ed.

Mean Density of the Earth.—The weight of the whole earth has been determined by several physical and astronomical considerations, and it has been found that our globe weighs between five and six times as much as an equal bulk of water. We express this by saying that the mean density of the earth is between 5 and 6. The rocks of the crust are on an average about two and a half times as heavy as water, so that the rate of the mean density of the crust to the mean density of the whole earth lies between 5 to 10 and 5 to 12, or may be put at 5 to 11. It follows from this that the interior of the earth must contain matter far denser than that which forms the crust.

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* Some geometers have thought that the results of observation can be best reconciled by supposing that the earth is not exactly a solid of revolution, and that the equator is not a circle but an ellipse whose longest diameter is between one and two miles longer than the shortest diameter. For a summary of their views see Nature, x. 160. Archdeacon Pratt has thrown great doubts on the necessity for such a supposition (see Figure of the Earth, 4th ed., 181). Sir W. Thomson supports it, Natural Philosophy, Arts. 796, 797.

We know nothing for certain about the way in which the materials of the earth are arranged, but an expression, due to Laplace, which will be given further on, represents very probably the law of the density of the interior. If we employ this expression to calculate the probable density at different depths, we shall find, taking the density of the surface to be 2·5—

Density	at depth of	250	miles	3·1
"	"	500	"	3·8
"	"	1,000	"	4·8
"	"	1,500	"	6·4
"	"	2,000	"	7·5
"	"	2,500	"	8·5
"	"	3,000	"	9·2
"	"	3,500	"	9·6
"	"	4,000	"	9·8

The densities of the principal metals are—Gold, 19·3; Lead, 11·3; Silver, 10·5; Iron, 7·8; so that the density half way down is about that of Iron, the density at the centre less than that of Silver.

Two explanations have been offered to account for the high mean density of the earth. It has been suggested that, far down below the surface, the enormous weight of the overlying rocks would alone suffice to compress the material of the interior, and make it as dense as observation shows it to be. It is, however, an open question how far we can go on increasing the density of bodies by increasing the pressure to which they are subjected. Experiments, as far as they have gone, seem to show that, as the pressure is increased, the density increases, but at a rate that constantly grows less and less. It is therefore possible that the effect of additional pressure in rendering a body more dense may become less and less till a point of approximate maximum density is reached, and that beyond that no increase in the pressure will add sensibly to the density.

Those who hold this view account for the high mean density of the earth by supposing that the interior contains a much larger percentage of heavy metals than the crust.

On the subject of the earth's density the reader may consult Lockyer's Elementary Lessons in Astronomy, Arts. 634—637; Airy's Ipswich Lectures, pp. 205—214; Maskelyne, Phil. Trans., 1775, p. 500; Cavendish, Phil. Trans., 1798, p. 469; Baily, Astronom. Soc. Monthly Notices, iv., 96; Phil. Mag., xxi. (1842), 111; Sir H. James, Phil. Trans., 1856, p. 591.

Internal Temperature of the Earth.—The temperature of the surface of the earth varies according to the time of day and the seasons; as we descend below the surface, we find the oscillations due to these causes to grow less and less, and at last we reach a point where they cease to make themselves felt, and the temperature of the rock is practically constant. A surface passing through all the points thus determined is called *the stratum of invariable temperature;* its depth increases, on the whole, from the equator to the poles, but many local variations are caused by circumstances such as unequal conducting power of the surface rock, and for this reason the depth of the invariable stratum does not follow any fixed law from place to place. At Greenwich it is found at a depth of 50 feet, and the temperature of the earth is there 49·5° Fah., or one degree higher than the mean temperature of the air.

When we pass below the stratum of invariable temperature, it has been found, wherever observations have been made, that the deeper we go the hotter does the earth become. The rate of increase determined in various cases varies between very wide limits, perhaps about 1° Fah. for every 60 feet of descent will be about the average of all the observed rates. The depth of the deepest point whose temperature has been noted falls considerably short of a mile, and observation therefore merely justifies us in saying that, for the moderate depths to which we have been able to penetrate, the temperature increases as we descend.

The reader may refer for details to Phillips, Phil. Mag., v. 446 (1834); Forbes, Trans. Royal Soc. of Edinburgh, xvi. 189 (1846); Angström, Upsala Nov. Act. Soc. Sci., i., 147 (1851); Hopkins, Phil. Trans., 1857, p. 805; Hull, Proceed. Royal Soc., xviii. 175 (1870), Quart. Journ. Sci., v. 14 (1868); Reports of the British Association Committee on Underground Temperature, 1868—1872; Sir W. Thomson, Trans. Royal Soc. of Edinburgh, xxii.

405 (1860); J. D. Everett, ibid., xxii. 429 (1861), xxiii. 21 (1861), Edinburgh New Phil. Journ., xiv. 19 (1861), Reports of British Assoc., 1859, Trans. Sect., 245; Silliman's Journal, xxxv. 17 (1863), Proceed. Belfast Nat. Hist. and Phil. Soc., 1873—1874, p. 41; Greenwich Observations, 1860, p. cxciii.

Inferences from the foregoing Facts.—Such being the facts we gather from observations at the surface, we have next to see how far they are in accordance with the hypothesis that the earth has assumed its present condition by cooling down from an intensely heated gaseous or fluid state.

It is of course open to any one to maintain that the earth came into being just as it is now, with the exception of those surface modifications which geology shows have been for a long time and are now going on; but the supporters of such a view, if there be any, will have to get over several very ugly objections. First, with regard to temperature, has it always been the same as now? In that case, since heat is constantly passing away by radiation, there must be some means of making good the loss, and keeping the interior at a constant temperature. No adequate means of bringing about this adjustment has yet been suggested. But if we suppose that the earth was once far more highly heated than now, we can understand that the inside must be hotter than the surface, because the heat passes off from the latter by radiation, and from the former by conduction through materials of very low conducting power. The only reasonable explanation, then, which has been offered of the cause of internal heat is, that the earth is, and always has been, a cooling globe, which is exactly what the nebular hypothesis supposes to be the case.

Again, with regard to shape. If any hold that the present figure is original, they are bound to give reasons why it is a spheroid and not a sphere, and why, of the innumerable spheroids possible, a particular one has been chosen rather than any other. No possible reason can be assigned for the preference; we can see no useful end that was to be served by giving the earth exactly its present ellipticity, or any possible harm that would result from its being more or less elliptical. But we can show that all these peculiarities of shape would probably follow as a matter of course, if the earth has consolidated from a fluid state.

For those who wish to know the grounds on which this statement is based, we offer a short outline of the steps by which mathematicians have been able to prove this point. If a mass of heterogeneous fluid, acted on by no force besides the mutual attraction of its particles according to the law of gravity, rotates about an axis, the following results have been arrived at respecting its shape and internal constitution.

(1) The external form is an oblate spheroid, whose axis is that of rotation.

(2) If a surface passing through all the points where the density is the same be called a surface of equal density, then all these surfaces are concentric spheroids, having the axis of rotation for a common axis. The ellipticities of the surfaces of equal density decrease from the surface towards the centre.

(3) Surfaces of equal density are also surfaces of equal pressure.

(4) The density increases along any straight line from the centre to the surface.

Now in order to apply these results to decide whether it is probable that the earth's present shape is due to consolidation from a fluid state, we must do this. We must take a body of fluid having the same mass and volume and rotating in the same time as the earth, calculate what would be its ellipticity, and see whether it comes out the same as the observed ellipticity of the earth. The actual process, however, is one of great difficulty and complexity. We could determine the ellipticity of the surface if we knew the law connecting the density at any point, and the distance of that point from the centre. The density at any point will depend upon three things, the material of which the earth is composed at that point, and the temperature and pressure at that point. We know none of these three, and, if we knew them all, we should not be much better off, for we are unable to say what density a given temperature and pressure would produce in a given material; we could say that temperature would tend to decrease and pressure to increase the density, but not to what extent. We are therefore obliged to assume some law of density, and see whether the results that follow from our assumption agree with those of observation. Laplace assumed that the law connecting the density and pressure within the earth was such, that the increase in pressure varies as the increase in the square of the density. In the case of a perfect fluid, that is a fluid in which there is no friction between the particles, the density is proportional to the pressure, or double the pressure and you double the density; while with Laplace's law, to double the density the pressure must be increased more than fourfold. There is an *à priori* probability in favour of such an assumption. The material of the earth, when it assumed its present form, had probably so far cooled down as to be pasty and viscous, so that there would be a good deal of friction between the particles, and therefore the force necessary to bring them closer together would be greater than in the case of a perfect fluid. This assumption led to the following result. If we denote by D_a the density at every point on a surface of equal density whose semi-axis is a, then

$$D_a = \frac{A}{a} \sin (qa) \ldots \qquad (1).$$

where A and q are constants, that is the same for all surfaces of equal density.

We have next to determine the numerical values of A and q; and this we do in the following way. If r represents the polar radius of the earth, we obtain the expression for the density at the surface by substituting r for a in equation (1), or

$$\text{Surface Density} = \frac{A}{r} \sin (qr).$$

Observation shows that the surface density is about 2.5, so that

$$\frac{A}{r} \sin (qr) = 2{\cdot}5.$$

Again, we can by a little calculation, frame from the general formula (1) an expression for the mean density in terms of A and q; this we equate to the value of the mean density obtained from observation. Thus we arrive at two equations, from which the numerical values of A and q are determined.

Further formulæ, which are too complicated to be introduced here, give the eccentricity in terms of A and q; and now that we know the values of these quantities, we can determine the value of the eccentricity which follows from Laplace's assumption, and see if it agrees with the observed value. When the calculations are made, the value obtained from theory is found to be almost exactly the same as the values given by several independent methods of observation.

As a further check on the correctness of the assumed law of density, we may determine what results it leads to respecting the variation of gravity at different points of the earth's surface and the amount of the Precession of the Equinoxes, and here again the calculated and observed values are closely in accordance with one another.

These remarkable coincidences are strongly in favour of the hypothesis of the earth's original fluidity, and no other theory has been propounded to account for the observed facts by the operation of natural causes. But there is not evidence enough to justify us in saying that no other satisfactory theory can be devised. Professor Stokes has pointed out that, for all we know to the contrary, there may be other laws of density which would give equally satisfactory results. He has shown that, in order to have the agreement we have arrived at between theory and observation, two things only are necessary. First, the earth's surface must be what is called a "surface of equilibrium," that is, one of the surfaces which a rotating fluid mass tends to assume when acted on by nothing but the mutual attraction of its particles. Secondly, the interior density may follow any law whatever, provided only that the surfaces of equal density are nearly spherical, and have a common centre and axis. The first condition is certainly and the second probably satisfied in the case of the earth, and hence, whatever be the law of the density of the interior, the observed and calculated values of the change in gravity and of the precession will agree. The tests, then, we have applied are not sufficient to establish the correctness of the assumption on which the truth of the fluid hypothesis is based, and it is possible that the earth may have assumed its present shape in some other way than by consolidating from a fluid state. At the same time, Professor Stokes admits that Laplace's law represents in all probability approximately the distribution of matter within the earth, and that the agreement of the results of calculation deduced from it with those of observation furnishes a certain degree of evidence in favour of the hypothesis of original fluidity.*

It is so important that the student should clearly realise how far known facts may be fairly said to be in favour of the earth's original fluidity, that we will repeat under somewhat a different form the line of argument just worked out.

If we start with the assumption that the matter composing the earth was once a fluid mass rotating about the present axis, mechanical considerations show that the form assumed on consolidation will be an oblate spheroid having the axis of rotation for its geometrical axis. The earth has, we have seen, this shape. If we make the further assumption that the matter in consolidating arranged itself according to the law of density adopted by Laplace, we find that the calculated values of the ellipticity, of the variation of gravity over its surface, and of the amount of precession, come out almost exactly the same as those obtained from observation.

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* Pratt, Figure of the Earth, 4th ed., Conclusion; Cambridge and Dublin Math. Journ., iv. 210.

The question then arises, do these coincidences warrant the conclusion that our two assumptions are necessarily true? They obviously do not, unless we can show that no other hypothesis leads to an equally close agreement between the results of theory and observation.

Now, curiously enough, it turns out that the variation of gravity and the amount of precession will be the same whatever be the law which governs the density of the interior, provided only that the external surface is a "surface of equilibrium," and the surfaces of equal density are spheroids of small eccentricity with a common centre and axis. Our earth is bounded by a surface of equilibrium, and there is every reason to believe that the arrangement of the interior must satisfy the second condition. Hence the surface variations of gravity and the precession tell us nothing about the law of density that obtains in the interior; they would remain exactly what they are even if the density followed a law different from that assumed by Laplace, and really the coincidences which obtain in their case between the theoretical and observed values, add nothing to the evidence in favour of Laplace's assumption. We are therefore thrown back on the eccentricity, and here there is the obvious objection that, though the fluid hypothesis does lead to a value the same as the actual one, it is yet perfectly conceivable that an equally satisfactory theory might be devised, which would account for the earth's present shape in some other way. But till some one shall point out what that other way was, and by what machinery it produced the earth's present shape, we are bound to look favourably on the fluid theory, because it does supply us with a definite mechanical process perfectly capable of effecting the observed result.

To this recapitulation we may add, that it is worthy also of note, that whatever the law of the internal density, it is necessary that the external shape of the earth should be that which a rotating mass of fluid assumes, or we should not have the requisite agreement between calculation and observation. This fact constitutes an antecedent probability that original fluidity has been the cause of the earth's figure.

We may fairly say then, that the hypothesis of the original fluidity of the earth is the only hypothesis yet propounded which furnishes a satisfactory explanation of the origin of the earth's figure, and that, till some better explanation is offered, we are bound to accept it as a highly probable provisional theory.

It is also in its favour that it does not stand on its own legs only, but is really part and parcel of the far wider Nebular Hypothesis, on behalf of which independent arguments might be urged.

Present State of the Earth's Interior.—Seeing, then, that it is likely that the earth was once wholly fluid, our next inquiry will be whether any part of it is still in that state, and, if so, how much?

Doctrine of a Thin Crust.—A very off-hand solution of this question was at one time thought sufficient. It had been found that for small distances below the surface the earth grew hotter the deeper we got into it; and if the heat went on increasing at the same rate, it was easy to see that at points not very remote from the surface a temperature must exist which would be quite sufficient *at atmospheric pressure* to melt the most refractory substances. It was therefore maintained that the interior of the earth must be necessarily in a state of fusion, and that the only supposition reconcilable with the known increase of heat downwards was that there was an outside solid crust not many miles thick, while below that the earth consisted of melted matter down to its centre. To explain this state of things, it was supposed that the solidification of the earth began at the outside, spread slowly downwards, and had not yet extended to any great depth. It was believed that volcanoes drew their lava from the great internal reservoir of molten matter, and that the phenomena of upheaval and the displacements of the stratified rocks were caused by upswellings of portions of the seething mass.*

The doctrine that the earth consists of a thin crust and a molten interior was at one time very generally accepted, and it is by no means certain yet that it is altogether false. It has, however, been opposed on various grounds, and some of the objections, it must be allowed, have considerable weight. It is easy to see that the arguments by which it was originally supported did not take into account several considerations, which, it is possible, might modify its conclusions very seriously; and other objections have been raised to it on mechanical grounds. We must now consider the arguments of those who oppose this view.

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* For a summary of these views see Cordier, Edinburgh New Phil. Journ., Jan., 1828, p. 273; Paris Mem. Acad. Sci., vii. 473 (1827).

In the first place, the doctrine of a thin crust involves the assumption that the temperature continues to increase to all depths at the same rate as had been observed near the surface. Sir W. Thomson has shown that it is perfectly possible that this may not be the case. He inclines to the belief that the temperature would increase at the rate of 1° Fah. for every 51 feet down to a depth of 100,000 feet or so, but that below that depth the rate of increase per foot would begin to diminish sensibly. At 400,000 feet the rate would be 1° for 141 feet; at 800,000, 1° for 2,550 feet, and so on in a rapidly diminishing ratio. Such, he thinks, is the probable representation of the earth's present temperature down to 100 miles, below which the whole mass is, whether liquid or solid, probably at, or nearly at, the proper melting point for the pressure at each depth. Sir W. Thomson has assumed in this investigation that no crust would be formed till the whole earth had cooled to a uniform temperature of 7,000° Fah. (which he takes to be about the average melting point of rock), that is to say, till the whole earth was just on the point of solidification. This and some other assumptions perhaps detract from the value of the result, still the investigation is of great importance, as showing the possibility of a state of things very different from that implied by the doctrine of a thin crust.*

Another oversight was committed in not taking into account the possible effects of pressure. Even supposing the surface rate of increase of temperature to be continued to all depths, yet pressure would increase at the same time, and it is perfectly possible that, under great pressure, substances may remain solid at temperatures far higher than would suffice to melt them at the surface. If the power of pressure to keep bodies solid be greater than the power of heat to melt them, the earth might be solid to the core even though the surface rate of increase of temperature should be kept up to the centre.

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* Transact. Royal Soc. of Edinburgh, xxiii. part i. p. 157; Thomson and Tait, Natural Philosophy, p. 689.

Unfortunately we know next to nothing about the relation between the fusing point of rocks and the pressure they are subjected to; but, as this is a question which will come before us again before long, we will give here what little can be said on the subject. It seems *à priori* likely that, if a body expands in melting, the fusing point will be raised by pressure; for the greater the pressure the greater will be the amount of energy required to force its molecules apart. Experiments have to a certain degree confirmed this inference, as will be seen from the result of Mr. Hopkins's investigations given in the following table:—*

Pressure in lbs to the sq. inch.	Fusing points of Spermaceti.	Fusing points of Wax.	Fusing points of Stearine.	Fusing points of Sulphur.
Atmospheric.	124°	148·5°	138°	225°
7,790	140°	166·5°	155°	275·5°
11,880	176·5°	176·5°	165°	285°

On the other hand, in some metallic alloys Mr. Hopkins failed to detect any elevation of the melting point by increased pressure. Mr. David Forbes has also pointed out that, in the case of Sulphur, the elevation of the fusing point goes on at a diminishing rate as the pressure increases; thus, between atmospheric pressure and that of 7,790 lbs. to the inch, it takes an increase of 141 lbs. to the inch to raise the fusing point one degree, but between 7,790 lbs. and 11,880 lbs. to the inch, it takes an increase of 409 lbs. to the inch to produce the same elevation; and he has suggested that, just as there is probably a point beyond which addition of pressure does not make a body denser, so there may be a similar limit beyond which the fusing point of a body is not raised by increased pressure.† The remainder of the experiments do not confirm this notion, for the tendency in Spermaceti is decidedly, and in Wax and Stearine slightly, in the opposite direction; but perhaps we can hardly reason from such easily fusible substances as to the properties of the more intractable materials of the earth. One thing, however, we may safely say. Supposing that at great depths below the earth's surface there is heat tending to produce and pressure tending to prevent fusion, our knowledge is not sufficient to enable us to say which, at any given point, will prevail.

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* Report of British Assoc., 1854, Transact. of Sections, p. 57.

† Chemical News, October 4th, 1867.

We are equally in the dark as to the effect of high temperature in altering the conducting power and specific heat of rocks.

Again, if we are to have a thin crust and a molten interior, the solidification of the earth must have begun at the surface; but we do not know that this was the case, it may have begun at the centre.

Whether solidification begins at the surface or at the centre, will depend on that relation between fusing point and pressure about which we are unluckily ignorant. If, during the time when the earth still retained a considerable degree of fluidity, portions of the outside became solid, or increased in density owing to loss of heat by radiation, they would sink down into the still fluid mass below. If, as they approached the centre, the increased pressure had a greater effect in preventing them from being fused than the increased temperature had in promoting their fusion, they would retain their solidity, and thus a solid nucleus would accumulate round the centre. This process would go on till the fluid portion had so far cooled down that it was too pasty to allow of any hardened portions of the surface sinking through it. The external half-fluid shell would then begin to cool by conduction, the superficial part would part with its heat most rapidly, and, since none of it could descend, an external crust would be formed. In this way we might arrive at an earth with a solid crust and a solid nucleus, and a shell of imperfectly fluid matter between. The gradual loss of heat by conduction might subsequently cause the intermediate shell to solidify, and the earth might thus become solid from surface to centre.

If, on the other hand, the influence of pressure in preventing fusion were less powerful than that of temperature in promoting it, the portions solidified at the surface would be again melted as they sank, and the earth would be kept fluid throughout, till it reached the pasty state, when an external crust would begin to be formed. But even in this case we should not be able to say what is the present thickness of the crust unless we knew the original temperature, the time elapsed since it began to be formed, the rate of cooling, and sundry other things, about all of which we are hopelessly in the dark. It is perfectly possible that the crust may not yet have attained any great thickness, or it may be that solidification has worked its way down to the centre.

It appears, then, that, assuming the earth to have come into its present condition by cooling from a melted state, it must have one of the three following constitutions:—

(1) It may consist of an external solid crust and the interior may be wholly fluid.

(2) It may consist of a central solid nucleus and an external solid crust, separated by a shell of imperfectly fluid matter.

(3). It may be solid throughout.

But we are altogether unable, with our present knowledge, to decide by direct reasoning which of these three states represents most probably the present constitution of the earth, or in the first and second cases to estimate the probable thickness of the crust. We must therefore see if any light can be thrown on the question by indirect methods.

Argument from Precession.—Among the attempts made in this direction, we must notice first the endeavours of the late Mr. W. Hopkins to determine what is the least possible thickness of the earth's crust that is consistent with the phenomena of precession and nutation. The actual calculations are exceedingly refined and intricate, but the following sketch will give an idea of his line of argument. The attractions of the sun and moon on the portions of the earth which bulge out at the equator are always producing slight displacements of the earth's axis, and these movements, combined with the earth's rotation, cause the axis to move in the following fashion. Take two straight rods, unite one end of one to one end of the other by a loose joint, and connect the other ends by a bit of string; then hold one rod perpendicular to the plane of the ecliptic, and move the other round, *keeping the string always tight;* the extremity of the second rod will describe a circle in space, and the motion of the rod itself will resemble in everything except speed the precession of the earth's axis. Nutation consists in small deviations first to one side and then to the other from the position which the axis would have if precession alone existed. It may be represented by supposing that the string in our illustration is slightly elastic, and keeps alternately lengthening and shortening itself a little. Under these circumstances, the path of the end of the movable rod will be like the edge of a disc with a slightly crimped or wavy outline, and this is the character of the path actually described by the extremity of the earth's axis in space. It is important to note that these movements are due entirely to the spheroidal shape of the earth, and would not exist if it were a true sphere. In Fig. 136, let *A B C D* be a section of the earth through its axis, *A E C F* a circle whose diameter is the polar axis; then, if we were to take away the protuberant portions of which *A B C E*, *A D C F* are sections, there would be no precession; if we were to take away the sphere *A E C F* the precession would be very much larger than it actually is, because the sphere *A E C F*, being rigidly attached to the protuberances, has to be carried round with them, and acts as a drag, preventing them from moving as fast as they would if they were not thus weighted. Now suppose that a portion, *G H K L*, of the central sphere is replaced by a mass of *perfect* fluid, the action of the sun and moon will not produce any precessional movement on this fluid, and, as there will be no friction between it and the external shell, the latter will slip freely over it. Under these circumstances it seems likely that the amount of precession would be larger than for an earth solid throughout. Now the amount of precession calculated on the hypothesis that the earth is solid agrees very closely with the observed amount, and Mr. Hopkins set himself to work to determine how much

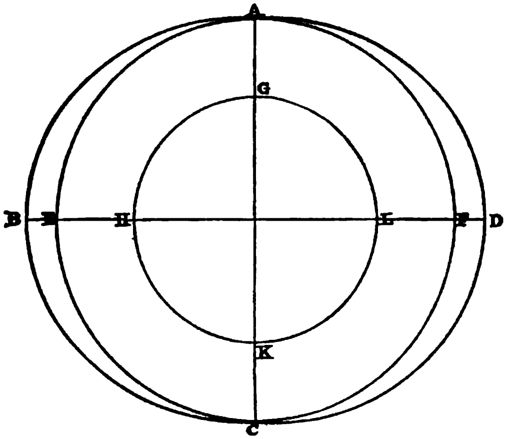

Fig. 136.

of the interior could become fluid without impairing this agreement. On the supposition that *the fluidity was perfect, and the change from the fluid to the solid part abrupt*, he found that the thickness of the crust could not be less than one-fourth or one-fifth of the radius.*

Argument from Rigidity.—The subject may also be approached in another way. The attractions of the sun and moon are greater on those parts of the earth that are nearer to them than on those which are farther off; the solid part of the earth is for this reason subjected to unequal pull, which keeps it in a constant state of strain. The same attractions will also tend to make the internal fluid portion bulge out on the side nearest the attracting body, and exert a pressure on the external shell tending to stretch the latter. We may try to determine what is the least thickness which will enable the crust of the earth to bear this strain and thrust, and prevent its being dragged or forced out of shape. This problem has been attacked by Sir W. Thomson.†

He supposes the earth to consist of a spheroidal, homogeneous, slightly elastic shell, filled with *incompressible* fluid, the transition from the solid to the fluid portions being abrupt; and on this hypothesis he has calculated to what extent the shell would be pulled out by the disturbing actions of the sun and moon.

It is not likely that the amount of distortion would be large enough to be capable of detection by direct measurement, but it might make itself sensible by its effect on the tides. If the crust is drawn up in the same direction as the water—that is, if there are tides in the solid part of the earth as well as in the ocean—the height of the tide can be shown to be less than if the earth were perfectly rigid; so that if we knew what would be the height of the tide on the latter supposition at a given spot, and find the observed height to be less than this, we have a measure of the extent to which the solid part of the earth has been pulled out by the tide-generating influence. Now Sir W. Thomson showed that, even if the spheroid were solid throughout and as rigid as glass, it would still give way to an extent, which would make the tides only about two-fifths as great as they would be if the earth were perfectly rigid; if the rigidity were that of steel, the corresponding reduction would be to about two-thirds. He concludes that a thin crust could not possess the requisite amount of rigidity, and puts down the minimum thickness that would suffice to resist the distorting influence at 2,000 or 2,500 miles. But he goes on to say that the distribution of land and water alters the effects of the diurnal and semi-diurnal tides to an extent which no mathematical analysis can estimate, and that we cannot therefore use any deviations which they show from their calculated amount as measures of the earth's want of rigidity; at the same time he thinks it very unlikely that these terrestrial disturbing causes can reduce these tides to two-fifths or two-thirds of the height they ought to have if the earth were perfectly rigid. He thinks, however, that the amount of the lunar fortnightly and of the semi-annual tide would not be affected to the same extent by the configuration of land and sea if observations of them were made at suitable points, and that they might be employed for the purpose of comparing the calculated and observed results. Unluckily, however, no sufficient observations of these tides have yet been made. It would seem then that, even if the assumptions by which Sir W. Thomson was enabled to deduce his results are justifiable, the observations necessary for applying these results to the actual case of the earth are just those which have not been made; and that till this defect is remedied, no conclusions can be arrived at.

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* Phil. Transact., 1839, p. 381; 1840, p. 193; 1842, p. 43; Report to British Association on Elevation and Earthquakes, 1847, pp. 45—55; Transact. of Cambridge Phil. Soc., vol. vi. part i.; British Association, 1857, Transact. of Sections, p. 70.

† Phil. Transact., cliii. (1863), 573; Natural Philosophy, sects. 832—834, 847, 848; Nature, v. 223, 257.

Sir W. Thomson has also investigated the effect of want of rigidity on the amount of precession and nutation. The observed amount agrees very closely with that obtained by calculation on the hypothesis that the earth is perfectly rigid. Any considerable want of rigidity would very materially alter the amount in most cases. But there are three arrangements under which the precession of an earth with a yielding crust would be approximately the same as for perfect rigidity. The first requires a compensating adjustment so very unlikely to be realised, that we may dismiss it at once; the second is incompatible with a thin crust; the third is, that the distortion should be very small in comparison with what it would be if the earth were fluid without. Now we will attempt to show by-and-by that if the transition from the solid to the fluid part of the earth is gradual and not sudden, this last condition may be satisfied. This argument from precession, then, is not conclusive.

Objections to the preceding Arguments.—Masterly as are the investigations just described from a mathematical point of view, it is to be feared that they have not contributed much towards the settlement of the question they were intended to decide. Some of the conditions they start with are so totally different from those of the actual case, that it is very questionable whether they can be fairly applied to the instance of the earth.

It cannot be supposed that Mr. Hopkins's fundamental assumption of a solid crust separated by a hard-and-fast boundary from a perfectly fluid interior represents even approximately the internal condition of the earth. The transition from one to the other must be extremely gradual, the interior portion of the crust will grow more and more soft till it passes into a pasty viscous state, and this sticky matter will become more and more fluid as we approach the centre, and may possibly at considerable depths approach perfect fluidity. Professor Hennessy* and M. Delaunay† have both expressed their opinion that the results deduced by Mr. Hopkins are for this reason not applicable to the case of the earth, and the former has raised further objections to his method. Mr. Hopkins himself did not by any means overlook this want of agreement between the actual and assumed conditions, and endeavoured to show that in spite of it his conclusions would hold good. He says that if C be the centre, $C\,S$ any radius of the earth, A a point on that radius above which the earth is solid, B a point below which all is fluid, and $A\,B$ the intermediate transitional portion, then if we take $S\,A$ to be the thickness of the crust it will give the precession too large, and if $S\,B$, too small; but there will be some intermediate thickness which will give the right amount, and this he calls the Effective Thickness of the crust. It is the depth of this Effective Thickness which he has shown cannot be less than 1,000 miles. All, then, which he has proved amounts to this, a shell of at least 1,000 miles thick must participate in the precessional motion. But this is a very different thing from saying that the whole 1,000 miles must be solid: possibly only a very small portion might be in this condition and the rest in a more or less viscous state, and yet the whole be carried round very nearly as if it were all solid, because the friction between the particles of the pasty part prevented them being dragged one over the other. Different parts of the viscous mass would be from time to time compressed and extended, but it seems perfectly conceivable that for all practical purposes the solid and semi-fluid portions of the crust might hang together as a whole.

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* Phil. Transact., cxli. (1851), 495; Geol. Mag., viii. 216; Nature, iv. 182.

† Comptes Rendus (July 13, 1868), lxvii. 65; Geol. Mag., v. 507.

The conclusions of Sir W. Thomson as to the Rigidity of the Earth have also been attacked by Professor Hennessy.[*] He has pointed out how seriously the hypothetical differ from the real conditions of the problem, and specially how the neglect of the pasty shell that must exist between the solid crust and the more fluid interior impairs the validity of the results. This pulpy stuff would act as a pad or buffer, and the work done by the disturbing action of the sun and moon on the internal portions of the earth, instead of being transmitted to the surface and altering its shape, would be used up "partly in producing small variations of density among the compressible strata of the nucleus, and partly in changing the shape of the yielding matter of the inner surface of the shell." By this means the deformation of the shell might be very small indeed, and the amount of precession the same as if the earth were solid throughout and perfectly rigid. Practically the observed amount of precession is rather less than it would be if the earth were perfectly rigid; some small distortion of the crust is probably therefore produced, and this we may take as the measure of that portion of the interior work which has managed to penetrate the buffer and make itself felt in the solid crust. A calculation made by Archdeacon Pratt furnishes an illustration of Professor Hennessy's objection.[*] Starting with Mr. Hopkins's assumptions about the interior of the earth, he shows that the internal fluid nucleus will be pulled by the attraction of the sun and moon, and will exert a pressure against the crust which tends to increase the precession; and that the effect of the want of rigidity in the crust will tend to decrease the precession. He then determines to what extent the surface must be elevated in order that these two modifying causes may destroy one another, if the crust be 800 miles thick, and this he finds to be 20 feet. A deformation of one-seventh of this amount would altogether abolish tides in the open ocean, and hence he concludes that the crust must be far thicker than 800 miles. Now if the internal fluid mass, instead of pressing against an unyielding crust, had a soft pad of semi-fluid matter to bury its nose in, we can readily imagine its energy

[*] Nature, v. 288. [†] Figure of the Earth, 4th ed., p. 135.

might be consumed in pushing this aside, and no pressure might be exerted on the crust; and if the crust, instead of being solid throughout, had a yielding lining, the work due to the external disturbing force might be expended on the lining, and give rise to no change in the shape of the surface. In such a case, as far as the causes mentioned are concerned, the precession would be unaffected.

Professor Hennessy's Views.—Professor Hennessy has attempted, in his paper in the *Philosophical Transactions* already quoted, a mathematical solution of the question now before us. It is impossible to convey any adequate notion of his way of handling the subject without more mathematics than are admissible here, but the following are his chief points:—

He objects at starting that all previous investigations had tacitly made an assumption that cannot be justified, namely, that the volume of the entire mass and the law of density of the earth have remained the same, or, in other words, that the particles of the original fluid mass underwent no change of position, during the process of solidification.

He then considers what would be the order of events during solidification. First, he thinks there would be much chemical action. When the chemical affinities of the materials had been satisfied, the mass would probably be in a state approaching perfect fluidity, and circulation would go on, the portions that had grown denser by cooling descending and the lighter portions ascending, till the whole had arranged itself in concentric shells whose density increased from the surface to the centre. When this state had been arrived at he thinks a surface crust would begin to be formed. Of course, when any piece on the outside had become solid, it would on account of its increased density tend to sink, but the three following causes would hinder its descent:—

1st. Each stratum into which it descended would be denser than the one above.

2nd. Each stratum would have its density increased by the passage through it of cooler portions from above.

3rd. The descending portions would have their densities diminished by the increase in the temperature downwards.

Under these circumstances he thinks that, though circulation would go on, it would be confined to the neighbourhood of the surface, and a crust might be formed; below the crust would be a shell of imperfectly fluid matter, and the interior might retain a high degree of fluidity. He believes that, even if from any cause the solid shell and fluid nucleus rotated at any time at different rates, yet that the friction between the two must be great enough to bring the motion of both to the same velocity of rotation. Finally he endeavours to determine the present thickness of the crust thus. He obtains an expression for gravity at the surface in terms of the radius and ellipticity of the fluid nucleus; and finds that if this expression is to agree with the known law of the variation of gravity over the earth, the crust cannot be less than 18 nor more than 600 miles thick. Professor Hennessy is also of opinion that it is impossible that consolidation can have begun at the centre, and that, even supposing any accumulation of solid matter there ever did take place, it must necessarily be melted again.

Mr. R. Mallet has arrived at the same conclusion by a different line of reasoning;* his views will be given more at length in Section III.

We cannot enter here any further into the question, but for additional discussion of these moot points the reader may consult Professor Hennessy, London, Edinburgh, and Dublin Phil. Mag., 3rd ser., xxvii. 376 (1845); Journ. Geol. Soc. of Dublin, 1849; Proc. Royal Irish Acad., iv. 337; Archdeacon Pratt, Figure of the Earth, Nature, ii. 264, iv. 28, 141, 344; Geol. Mag., vii. 421; Nature, iv. 45, 182, 383; Professor Haughton, Transact. Irish Acad., xxii. pt. 1, p. 251; D. Forbes, Geol. Mag., viii. 162; P. Scrope, Geol. Mag., vi. 145; D'Archiac, Histoire des Progres de la Geologie, i.; Thomson and Tait, Natural Philosophy, Appendix D.; Major-Gen. Barnard, Smithsonian Contributions, vol. xix. No. 240.

The only conclusion, if we can call it a conclusion, that it is safe to come to in the present state of our knowledge is, that it is highly probable that the earth has cooled down from a state of igneous fusion, but that there is not evidence to decide whether any of it, and, if any, how much of it, still retains its original liquidity.

Chemistry of the Early History of the Earth.—Some speculators have attempted to push their way back to periods of the earth's history even more remote than those we have been noticing. Beginning with the time when, owing to the intense heat, the chemical elements of the materials of the earth existed in an uncombined state, they have tried to trace out the steps of the process by which their combination was brought about, and the first rude outline of a solid globe was shaped out. The conclusions come to by different authors on this subject have hitherto been so utterly at variance with one another, that it almost looks as if the time had not yet arrived when we can profitably indulge in speculations of this nature.* Some speculations of Mr. Lockyer's, of a more promising character, will be noticed further on.

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* Phil. Transact., clxiii. (1873), 160.

SECTION II.—CAUSE OF UPHEAVAL AND CONTORTION.

We have seen reason to believe that the uplifting of rocks laid down beneath water, by which sea-bottoms have been converted into dry land, and the tilting, folding, contortion, and faulting, which observation shows these rocks to have undergone, are all due to some common cause. We have now to inquire how the force was generated which produced these movements. Reasons have already been given for believing that the disturbing force was, in very many cases at least, of the nature of a *horizontal thrust.* The phenomena of widespread and excessive contortion can be explained only on this supposition, and the lesser disturbances are so intimately connected with these grand movements, that it seems likely that both must be due to the same cause.

Certain, however, of the observed displacements, taken by themselves, are capable of explanation on the supposition that they were caused by a force *acting from within the earth vertically upwards;* and, though it is extremely doubtful, for reasons already given, whether this method has been ever employed in nature, it is only fair that the reader should be put in possession of the theories which have been started to show how this vertical up-thrust may be caused.

Sense in which Elevation is used.—It is somewhat unlucky that the words "upheaval" and "elevation" should have become so thoroughly rooted in geological nomenclature in reference to the movement of the earth's surface, that it is now scarcely possible to drop them. The first is decidedly objectionable, for it distinctly implies that the producing cause was a force acting vertically upwards, which it certainly was not in some cases, and perhaps was in none. If ever we employ these terms, it must be understood that we use them simply to indicate the carrying up of rocks from a lower to a higher level, and not in the least to suggest the direction in which the force acted by which the movement was effected.

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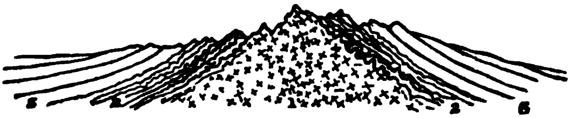
* De la Beche, Researches in Theoretical Geology, chap. i; Sterry Hunt, Quart. Journ. Geol. Soc., xv. 488; Geol. Mag., iv. 357, 426, 477, 525, v. 49, 106; David Forbes, ibid., v. 92, 106.

General Structure of Mountain Chains.—Before we go any further, it will be desirable that the reader's ideas should be clear on two points: first, what the arrangement of the rocks in a mountain chain* is not like; and secondly, what it is like. In many books he will find the general section of a mountain chain to be such as is shown in Fig. 137.

We see in the section a central nucleus of Granite, and from this the rocks dip away on either side in the same direction as the slope of the ground. The sketch gives the idea that the Granite has been driven up from below, and has thrust aside the rocks on either flank. There is no mountain chain known which has a section at all approaching this. The section in Fig. 138, though it fails to convey any adequate notion of the amount of crumpling, inversion, and smashing that is very frequently met with, gives a much fairer general idea of the disposition of the rocks.



1. Granitic Rocks. 2. Foliated Schists. 3. Unaltered Rocks.

Fig. 137.—What a Section across a Mountain Chain is not like.

The strata have not been simply bent up into a *single* boss, but have been folded, crumpled, and dragged over along a *number of lines* ranging roughly parallel to one another; and in many cases so far from the dip being *outwards* on either side of the range, it is directly in the opposite direction, the rocks plunge at high angles on both flanks *into the hill*, and a section of them shows something like the plaits of an open fan, the handle of which lies deep down in the centre of the mountain. Granite appears in several belts, but these show no signs of having been thrust up through the surrounding rocks. On the contrary, the rock shades off insensibly into foliated schists, and these melt away in unaltered rocks.

Mr. Hopkins's Theory.—We have already mentioned Mr. Hopkins as one of the ablest supporters of the vertical-upthrust explanation. The machinery he employed for producing the elevatory force was a body of fluid matter like lava, in a cavity below the surface, which under the influence of increasing heat, gave off elastic gas, and the pressure of this gas was supposed to bend up the overlying rock till it was strained to the breaking point. There is very little evidence for the existence of the internal lakes of fused, gas-yielding matter required by this theory, but, waiving this objection, we have already pointed out what seems to be its weak points in Chapter IX. p. 380. Mr. Hopkins's knowledge of the facts he attempted to explain seems to have been very imperfect. He speaks, for instance, of anticlinal and synclinal lines occurring with alternations of rapid and opposite dips at *intervals not exceeding a few miles.* If he had said every hundred yards or so, it would have conveyed a far more correct notion of the real facts in many

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* Using the term in the restricted sense applied to it in the preceding chapter.

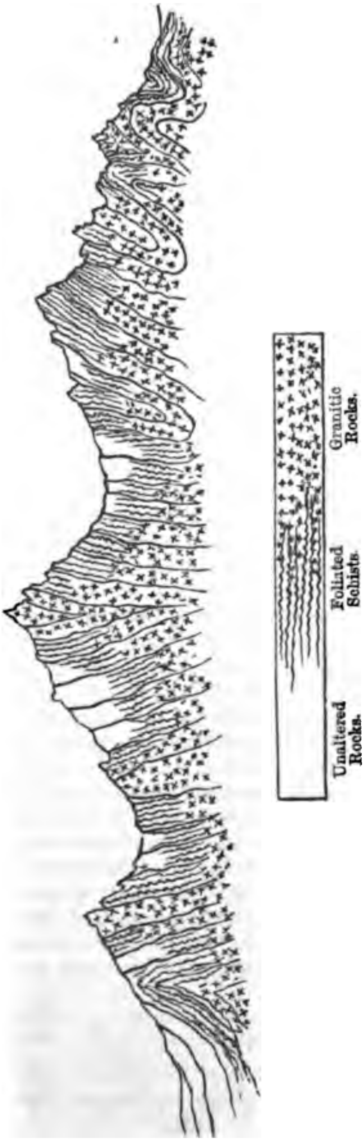

Fig. 138.—General Character of the Section across a Mountain Chain.

cases. His conviction, too, that all narrow, steep-sided valleys were rents in the crust, led him sadly astray. His beautiful mathematical investigations have, on account of his limited geological knowledge, not led at present to any useful results; but they may yet bear good fruit, and geologists will probably some day thank him for the attention he has given to the subject.

Theory of Scrope and Babbage.—Next comes a very ingenious speculation, originally suggested by Scrope,* and afterwards struck out independently by Babbage.† By the deposition of sediment on sea-bottoms an area, which before the deposition began formed part of the earth's surface and had the temperature of the surface, is gradually buried under a cover, constantly increasing in thickness, which checks the escape of the heat from within. The temperature of the rocks of this area will therefore be raised, and the rocks themselves must expand. The resistance to expansion will be less in a vertical than in a horizontal direction, and hence the area will bulge up and cause elevation of the rocks resting upon it. It is evident that this explanation accounts only for vertical elevation, and makes no provision for contortion or any form of compression; in fact the elevations produced by it would be bosses, the strata of which would be arranged in concentric domes, like that in Fig. 137, which, as we have pointed out, is a structure found in no mountain chain yet examined. Even then supposing some small local elevations may be due to this cause, it is quite inadequate to produce the larger disturbances which the crust exhibits.

There is another weak point about the theory. During the accumulation of many thick bodies of sedimentary rocks, the sea-bottom was gradually sinking. It makes no provision for this. It may explain vertical uplifting, but does not allow of subsidence during deposition.

Theory of Sir J. Herschel.—Sir J. Herschel ‡ threw out the hint that the mere weight of a thick mass of sediment might cause the part of the crust on which it rested to bend down, and the portions on either side to swell up. This would require the crust to be remarkably thin and yielding, and till this is shown to be the case the explanation cannot be admitted.

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* Volcanoes, p. 271, note.

† Proceedings Geol. Soc., ii. 74; Ninth Bridgewater Treatise, Note G, p. 209. See also Captain Hutton, Geol. Mag., x. 166, xi. 22; Nature, ix. 61; Rev. O. Fisher, Geol. Mag., x. 248, xi. 60, 64.

‡ Proceedings Geol. Soc., ii. 548, 596; Ninth Bridgewater Treatise, Note I, p. 225.

Intrusion of Granite.—Another explanation of the cause of the elevation of mountain chains, at one time very much in vogue among geologists, and adopted by Mr. Scrope, is as follows.*

In a very large number of cases a mountain range has a central axis of Granite or some Plutonic rock. This central mass was supposed to have been forcibly intruded in a semi-fluid state from below, and to have shouldered off on either side the rocks through which it forced its way. The intrusive matter was supposed to have been driven up by local increase of heat, which caused it to expand till the rocks above were no longer able to hold it down. Following the views put forward by himself and Mr. Babbage, Mr. Scrope accounts for the accumulation of heat by the deposition of a thick mass of strata above the spot where it occurred. It is clear that this process would give rise to tilting, and result in the formation of a ridge from which the beds would dip away on either side, as in Fig. 137, but it would not directly produce contortion. Mr. Scrope endeavours to show that lateral pressure would result indirectly in two ways: first, the molten matter injected into fissures would, if urged up with sufficient force, press laterally against the walls; and secondly, he thinks it possible that portions of the rocks, which were shoved aside by the intruded mass, might slide down its inclined flanks, and get crumpled up in the motion. In the first case the cause seems scarcely sufficient to do the work assigned to it. The sort of motion required in the second case seems hardly likely to occur.

This theory, too, fails to account for the violent contortions which not unfrequently are met with far away from any mass of Plutonic rock. Further, there is good reason to believe that the Granitic axes of mountain chains are not intrusive rocks at all, but simply portions of the very rocks that compose the flanks of the range converted by intense metamorphism into Granite.

These and other explanations, which we have not room specially to notice here, all fail to provide us with the horizontal thrust, which alone seems competent to produce contortion. We now pass to the only hypothesis which is satisfactory on this point, and is capable of giving rise at the same time to vertical upheaval and horizontal compression.

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* Volcanoes, chap. xii. See also Darwin, Transact. Geol. Soc., 2nd ser., v. 601.

Contraction Theory.—The contents of the last section seem to show that at present we have not knowledge enough to enable us to form a positive opinion on the questions, whether any part of the earth is fluid, and, if so, what is the thickness of the solid crust.

One point, however, has been established—the interior of the earth is hotter than the outside; and since it is very highly probable that the whole earth was once much more intensely heated than now, and that the present internal heat is only what is left of the original temperature, we arrive at a further fact, which has an important bearing on the questions to be discussed in this section, namely, that the earth always has been and still is a *cooling* globe, and, if a cooling globe, it must also be a *contracting* globe, if the materials of its interior are at all analogous to those which form its surface.

Further, it is almost universally true that the amount of shrinking produced by the loss of a given degree of heat (the coefficient of contraction), is larger when the body is at a high than when at a low temperature. Thus if a rod shortened by 1-100th of an inch when it passed from 212° to 211°, it would not shorten so much, say only 1-300th, when its temperature was reduced from 90° to 89°. From this it follows that since the interior of the earth—it matters not whether it is solid or fluid—is hotter than the outside, it must shrink faster than the outside. Practically the outside crust has so very little heat to lose, that it may be said not to shrink at all, while the hotter nucleus is gradually drawing away from it. If the crust were in this way left without support, it must crush in by its own weight, and the crushing force on any portion in a cross section of it can be shown to be equal to the weight of a column of rock which has that portion for its base and half the earth's radius for its height.* Pressure like this is far more than sufficient to smash in the most unyielding materials known, and the crust could not sustain it for a single moment. It must therefore follow the nucleus down. The only possible way in which it can do this is by its being crumpled into folds. It is as if we were to make a paper case that would just hold an orange of a certain size, and then try to make it fit closely over a smaller orange, we could evidently succeed only by wrinkling the paper. An old dried apple also furnishes an excellent illustration of the process. As drying goes on the fruit shrinks, but the skin does not: the latter accordingly, having to accommodate itself to the diminished nucleus, becomes puckered into wrinkles. According to this theory, then, the normal state of the earth's crust ought to be a crumpled one, and so it is. Where the force acted with concentrated energy along certain lines, or along lines of weakness, portions were ridged up into long narrow prominent protuberances, out of which mountain chains were afterwards carved by denudation. Here, too, owing to the intensity of the action, the rocks would be violently contorted. We have seen that excessive contortion is invariably found in lofty mountain chains. Possibly where the folding was more gentle, broad arches and troughs were produced, which gave rise to continents and oceanic depressions. We have already shown that the disturbances which the rocks of the earth's crust have undergone have been many if not all of them produced by forces acting in a horizontal direction, but we were not then able to explain how the thrust was generated. We can now see that we have, in the unequal shrinking of the cool crust and hot nucleus of the earth, a cause quite adequate to give rise to these horizontal compressions.

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* Rev. O. Fisher, Transact. Cambridge Phil. Soc., vol. xi. pt. 3; R. Mallet, Phil. Transact., clxiii. (1873), 173.

The notion that the earth's contraction has been the cause of the displacement of the rocks and the elevations of the surface seems to have occurred first to Descartes (Ed. française, 1668, p. 322). It was advocated by Constant Prevost[*] and Élie de Beaumont,[†] but the latter unluckily tacked on to it an untenable hypothesis, which served rather to bring it into disrepute. It was the favourite theory of De la Beche,[‡] and is adopted by a large number of the geologists of the day.[§]

Remarks on the Contraction Theory.—As far as mountain-building goes, no objection of any weight has been urged against the contraction theory. But when we apply the same explanation to the formation of continental areas and oceanic depressions, several difficulties present themselves. Mr. R. Mallet, while he strongly advocates the view that mountain chains were formed by the thrust due to contraction *after the crust had reached a certain thickness and rigidity*, thinks that this force is far too local in its range to be able to be transmitted across such vast areas as continents and oceans. The outlines of these, he believes, were marked out by broader foldings, which gave relief to the crust *at an earlier period of the earth's history, when the crust was very thin*. Professor Dana has also attempted to explain on this supposition several facts in the distribution of the great surface inequalities of the earth, such as the proximity of mountain ranges to coast lines, and the relation of the height of the range to the depth of the ocean facing it. Some of his generalisations are perhaps open to question, but he has suggested points well worth careful consideration.*

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[*] Bull. Soc. Geol. de France, xi. 183 (1840); Comptes Rendus, xxxi. (September, 1850), 461.

[†] Notice sur les Systèmes de Montagnes (Paris, 1852); Hopkins, Anniversary Address, Quart. Journ. Geol. Soc., vol. ix.

[‡] Geological Observer, p. 730; Researches in Theoretical Geology, p. 121.

[§] Mather, Silliman's Journal, 1st ser., xlix. 284; Dana, ibid., 2nd ser., ii. 352, iii. 94, 176, 380, iv. 88; 3rd ser., v. 423, vi. 6, 104, 161.

Professor Le Conte has raised the further objection that an arch broad enough to form a continent 3,000 to 6,000 miles across, or a trough that would hold an ocean like the Pacific, 10,000 miles broad, could not, even if the crust were several hundred miles thick, sustain itself; the arch must break down and the depression break up.† This objection hardly applies, because the crust does not sustain itself; indeed no segment of it could possibly stand unless it were supported underneath. He prefers to account for the formation of continental and oceanic reliefs by the hypothesis that the conducting power has been greater along some radii than along others. Some portions of the earth would then cool and contract faster than others; the first would sink down into oceanic depressions, while the second would be left standing up as continental tracts. Archdeacon Pratt ‡ adopts a similar view, on the ground that the mass of the earth is found in some cases to be denser beneath the ocean than beneath the land, and to be least dense beneath great mountain chains. If the facts adduced by Archdeacon Pratt turn out to be generally true, they are certainly in favour of this view.

We may notice that Mr. R. Mallet has shown that a deficiency of matter beneath great mountain ranges is just what the contraction theory necessarily leads to; while, if elevation were due to the swelling up of molten matter from below, the reverse ought to be the case (see his paper already quoted, p. 156).

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* See his papers quoted on p. 507, and his Manual of Geology, pp. 9—38, and 731—737. Also Rev. O. Fisher, "On the Inequalities of the Earth's Surface viewed in Connection with the Secular Cooling." Trans. Cambridge Phil. Soc., xii., part 2.

† Prof. James Le Conte, Silliman's Journ., 3rd ser., iv. 345, 460.

‡ Phil. Transact., clxi. (1872), 335; Figure of the Earth, 4th ed., p. 201.

If we adopt the supposition either of Mr. Mallet or Archdeacon Pratt, we must also admit that all the great leading features of the earth's surface were established at a very early stage in its consolidation, and have not materially altered since. There are some facts in the past history of the earth which are hard to reconcile with this view, but, as we have seen, it has a considerable weight of authority on its side.

Professor Shaler uses the contraction of the earth to explain the formation of continents and mountains in a somewhat different way from any yet noticed. He thinks the methods of formation of the two must be different. Continents he believes to be produced by broad foldings *affecting the whole thickness of the crust.* He accounts for the sharper wrinkles of mountain chains in the following way. The exterior part of the crust is and has been for a long time at the same temperature as the atmosphere, it therefore loses no heat and does not contract at all. But a deeper layer contracts sensibly, and to compensate for this the superficial portions of the crust must wrinkle up. According to him it is this *crumpling of the outer shell of the crust* which is the cause of mountain elevation.*

In conclusion, while we admit that the contraction hypothesis leaves some points to be still cleared up, we are yet justified in looking upon it as the most consistent and satisfactory explanation yet put forward of the cause of the disturbances of the earth's crust. At the same time it would be rash to say that it is the only cause; some of the other moving forces suggested may have been the means employed in certain cases.†

SECTION III.—ORIGIN OF THE HEAT REQUIRED FOR VOLCANIC ENERGY AND METAMORPHISM.

The next posing question for us to take up is, What gives rise to the heat which is required for the production of volcanic eruptions, metamorphism, and allied phenomena?

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* Geol. Mag., v. 511.

† For an ingenious explanation of the cause of some of the inversions that are found along the flanks of some mountain chains, see Medlicott, Quart. Journ. Geol. Soc., xxiv. 34; and Memoirs of the Geol. Survey of India, vol. iii. pt. 2.

Metamorphism and Lava, both Effects of the same Cause.—We have seen reason to believe, that the process which has imparted to the rocks usually classed as Metamorphic their crystalline texture and other peculiarities, will, if carried far enough, result in the production of fused rock underground, and that, if this molten stuff be driven up to the surface, it will flow out as Lava. The source of volcanic activity and of metamorphism we may assume, then, to have been the same, and we have to do two things: first, to find heat enough to bring about, in combination with other agents, metamorphism and fusion; and then to provide machinery competent to lift the fused matter to the surface.

Explanation on Hypothesis of a Thin Crust.—We have already seen how easily the doctrine of a thin crust solved the problem. The melted matter was ready to hand, and the fracturing and sinking down of the crust pumped it up.

But this explanation falls to the ground unless the crust is thin, and as that is a very doubtful point it cannot be accepted as satisfactory. There are besides several well-known facts that tell somewhat against it. The lavas of different vents differ considerably from one another, and often seem to be somewhat related in composition to the rocks through which the eruption has burst its way; if all lava came from one general reservoir, one would expect it to be more uniform in character. Again, there appears to be often no connection whatever between two vents very close to one another; the lava standing at different levels in the two, and in one being in gentle and in the other in violent ebullition. Such a fact, though not altogether incompatible with the vents opening into the same great internal tank, does not lend support to such a view. A more satisfactory answer to the second part of the problem supposed that water found its way by percolation down to the molten interior, and, being suddenly converted into steam, burst through the overlying rocks, flashed out in explosions, and forced up the lava.

Mr. Hopkins's Theory.—Independently then of the fact that it is very doubtful whether the crust is as thin as the explanation just described requires, it is unsatisfactory on other grounds. The advocates of a very thick crust propounded several others in its place. Mr. Hopkins supposed the solid part of the earth to contain hollows filled with matter still in a state of fusion, and he supposed these hollows to have arisen in the following way. When an incrustation had begun to form at the surface, the expansive force of the contained gases would every here and there tend to fracture the thin crust; and when areas of weakness had been once established, the gases would prefer to work their way out by apertures already in existence, even if they had to travel considerable distances to reach them, rather than to break open fresh points of discharge. Thus the crust would be parcelled out into disturbed and undisturbed districts, and solidification would extend downwards faster in the latter than the former. The under side of the crust would thus come to have inverted hollows over its surface, and the edges of these might extend down to the central solid nucleus if there was one, or unite beneath if the interior was wholly fluid, and so portions still liquid would be enclosed in the generally solid crust. Sir W. Thomson believes that the outer portion of the earth has a similar honeycombed structure.

Assuming that the method of solidification supported by Mr. Hopkins is probable, his hypothesis still fails to explain some of the leading facts of volcanic action. According to it there seems no reason why the internal fiery lakes, and the volcanoes that they feed, should be arranged according to any law; one would expect to find them dotted about haphazard. But one of the most striking facts about volcanoes is the way in which they are arranged in lines, either coincident with or parallel to lines of great elevation. The great volcanic belt that runs along the mountain chain formed by the Rocky Mountains and the Andes is one instance. The omission to account for this fact is a very weak point in the explanation. Again, the theory does not furnish a very satisfactory explanation of the alternate periods of repose and activity exhibited by volcanoes. One could understand a cavity being pumped out and there being an end of all eruption from it; but why it should discharge a part of its contents, then rest awhile, and then begin discharging afresh, it is not easy to see; and if it was once emptied, what is to fill it again? Such objections may not be fatal, but they naturally arise, and till they are met, the hypothesis cannot be said to be satisfactory.

Explanations of Mr. Scrope and Rev. O. Fisher.—Other authors will have it that below a certain depth the whole or portions of the crust are just verging on fusion, and that any change in temperature, or pressure, or both, may turn the scale and convert solid into melted matter. Mr. Scrope has supposed that sometimes the requisite increase of heat is caused by the accumulation of thick masses of sediment in a way already described; and that sometimes liquefaction may have been brought about by relaxation of pressure where the overlying rocks have been fissured or uplifted.* Mr. Mallet has shown that the amount of heat generated on the first supposition is not sufficient to produce the amount of volcanic action that is actually going on (note to his paper quoted below). The Rev. O. Fisher adopts the latter view; he maintains that, whenever the contraction of the crust raises a zone of rock into a mountain chain, the rocks underneath have no longer the weight of that zone pressing on them, and, if it was only pressure that kept them solid, they would pass into the liquid state.† This hypothesis accounts for the association of volcanoes with lines of elevation.

However satisfactory in other respects these and similar explanations may be, they cannot rise above the rank of speculations until the fundamental assumption with which they start is securely established.

While speaking of Mr. Scrope's speculations, we must not forget to mention that he did inestimable service by showing that, whatever be the origin of lava, the force that raises it to the surface is undoubtedly the expansive power of steam.‡ There is no difficulty in obtaining water; very nearly every one of the known active volcanoes is situated near the sea, and percolation would furnish a plentiful supply.

Sterry Hunt's Theory.—Dr. Sterry Hunt has put forward the following view of the present state of the earth's interior, and the origin of metamorphic and volcanic action. He believes that the earth consists of an exterior shell of sedimentary deposits, a solid anhydrous nucleus still highly heated, and between the two a zone of matter derived partly from the nucleus and partly from the outside shell, permeated by water holding siliceous and aluminous matter, carbonates, sulphates, chlorides, and carbonaceous substances, and raised to a temperature not necessarily very high by the heat from within. Under these circumstances

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[*] Volcanoes, pp. 265—275; Geol. Mag., v. 537.

[†] Transact. Cambridge Phil. Soc., xi.; Geol. Mag., v. 493.

[‡] Volcanoes, pp. 37, 116; Geol. Mag., vi. 196.

he maintains, on the strength of many experimental results, that the matter of this zone would be in a state of hydrothermal fusion, and that it would be converted, according to circumstances, into the various forms of Metamorphic, Plutonic, and Volcanic rocks. He adopts the Scrope-Babbage theory that thick deposits of sediment check the escape of internal heat; and, wherever this occurs, the reactions in the intermediate zone are increased in activity, and volcanic eruptions, upheaval, and other allied phenomena, result. For details of this elaborate theory, the reader must consult the papers quoted below.*

Mr. R. Mallet's Theory.—There is one very significant fact, which all the explanations hitherto glanced at have failed to notice. Metamorphism is always accompanied by contortion, and in many cases, perhaps always, it increases in intensity as the crumpling grows more violent and complicated.†

We have also seen how persistently volcanoes range themselves along mountain chains, that is, along belts of excessive contortion.

It seems, then, that not only are Metamorphic, Plutonic, and Volcanic action closely allied, but that contortion belongs to the same family. We have got at a fairly satisfactory explanation of the cause of contortion; will the machinery which produced it also furnish us with the heat whose origin we are in search of? Mr. R. Mallet has attempted to show that it will, in a very remarkable memoir,‡ of which we must attempt to give an abstract.

His ideas about the order of events during the passage of the earth from a gaseous into its present condition are as follows:—

1st Stage.—The chemical elements of which the earth is made up, existed uncombined in a state of gas, and the first step was the union of these into combinations similar to those we find in the globe at present.

2nd Stage.—When a state of chemical equilibrium had been established, the earth would be wholly fluid; the surface cooling would be more rapid at the poles than over the tropics, and in this way currents would be set up, but they would be superficial, and would not be sufficient to establish anything like an equality of temperature through the mass, so that the interior would be much hotter than the outside. Cooling would go on by radiation from the surface very rapidly on account of the high temperature, and a solid crust would begin to be formed round the poles, and spread both ways to the equator. The crust would pass gradually downwards into a shell of viscous matter, and this would graduate into the more fluid interior mass. He sees no reason to doubt the power of the crust to hold together, in spite of its small thickness, on the following grounds. His experiments on the cooling of slags show that a crust is formed round the fused mass when the temperature is very little below that of fusion, and the density of the crust differs very slightly from that of fused slag. Hence it is likely that in the case of the earth the density and temperature of the first-formed crust differed so little from that of the still fluid matter below, that there would be no very strong tendency for the solidified portion to sink, certainly not enough to overcome the resistance to sinking caused by the viscosity of the matter immediately beneath it. As Sir W. Thomson has pointed out, the boiling up of gases would probably cause the crust to be full of cavities, and this might give it buoyancy enough to keep it up.

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* Canadian Journ., 1858, p. 203; Quart. Journ. Geol. Soc., xv. 488; Comptes Rendus, June 9, 1862; Dublin Quart. Journ., July, 1863; Silliman's Journ., 2nd ser., xxxvii. 255; xxxviii. 182; 3rd ser., v. 264; Geology of Canada, 1863, pp. 643, 669; Report, Geology of Canada, 1866, p. 230; Geol. Mag., vi. 245.

† For one admirable instance, see Geikie, Transact. Edinburgh Geol. Soc., ii. 293, 294.

‡ Phil. Transact., clxiii. (1873), 147; Proceedings Royal Society, xxii. 328. See also The Eruption of Vesuvius in 1872, by Prof. Luigi Palmieri, translated by Robert Mallet; and Scrope, Geol. Mag., xi. 28.

3rd Stage.—After a time, but while the crust was still thin, the fluid nucleus would begin to contract faster than the crust, and the latter would have to accommodate itself by crumpling. He puts it forward as a conjecture, though he thinks a very probable conjecture, that the deformation of the crust at this epoch was effected by broad folds, and that by this means the great leading geographical outlines which the earth possesses at the present day were then impressed upon it; that the main continental areas and oceanic depressions were then marked out and have remained substantially the same ever since. Where contrary flexures occurred at the junction of continents and sea-basins, lines of fracture were formed, and lines of weakness established which have continued to be lines of weakness ever since. The surface he believes at that time to have been still too hot to allow of permanent accumulations of water on it, but comparatively cool water may have fallen, to be driven off as vapour, and precipitated afresh elsewhere, and so there may have been a constant succession of torrential rains and deluges; at the same time the rapid transfer of heat from the interior may have suddenly heated the cooled portions of the surface, caused them to fly and crack, and so produced great ruin and shattering of the crust. By such powerful denuding agencies he thinks the so-called "azoic" rocks may have been formed.

4th Stage.—The crust so far increased in thickness that there was a very material difference between the rate of its cooling and that of the fluid nucleus, and it became in consequence subjected to enormous tangential pressures, as the shrinking away of the nucleus tended to deprive it of support. It was now thick and stiff enough to transmit these compressions within itself, and the consequence was that it became ridged and doubled up into great projecting wrinkles, which were afterwards to be licked into shape by denudation, and become mountain chains. The crust would give way most readily along the lines of weakness already established, and this is the reason why great mountain ranges are found along sea-coasts.

5th Stage.—The crust had become so far thickened and rendered so rigid, as not to allow of the wrinkling that characterised the last stage. The shrinking of the hot nucleus still gave rise to tangential compressions, and the crust was obliged to yield to these in some other way; and relief was now afforded by crushing to powder the rocks of which it is composed. It is the special object of the paper to show that heat is generated by the crushing, and that we have here a source amply sufficient to supply all the heat necessary for the production of the known phenomena of volcanic action.

The effect of this crushing will be to produce belts, more or less tending to be vertical in position, of smashed and crushed rock. Down these water finds its way, and is absorbed by the pulverised mass, and then, if the temperature generated be high enough, a mixture of fused or partially fused rock and high-pressure steam is generated, which is forced up by the expansion of the steam,. and raised to the surface as lava. The experiments of Daubree have shown that water will make its way through capillary pores of rock in the face of a high opposing pressure of vapour, and have disposed of the objection that, if the pressure was sufficient to raise the lava, it would also prevent the access of water.

For the elaborate experiments, calculations, and estimates by which Mr. Mallet has endeavoured to show that the heat produced by crushing would be sufficient to produce the effects assigned to it, the reader must consult the original papers.

There are many facts about volcanoes that are satisfactorily explained by this theory. The rocks would yield most readily, the crushing would go on to the greatest extent, and the largest amount of heat would be generated along the old established lines of weakness, and hence we get a reason why volcanic vents follow lines of mountain elevation. Crushing would not go on uniformly, but at intervals; it would only take place when the accumulation of pressure had reached a point where the rock was able to resist no longer. Hence volcanic eruptions will be separated by intervals of rest. The production of an eruption also requires a certain balance between the supply of water and heat. If the former be in excess, the volcano may be either permanently or for a time drowned out, or its activity very much reduced.

The theory has the following additional recommendations. It has the merit of simplicity; it calls in no hypothetical agencies, the existence of which rests only on supposition, for it merely requires that the interior of the earth should be hotter than the outside, which it almost certainly is, and the co-operation of gravitation. It puts volcanic action in the light of a beautiful compensating arrangement. If the crust were perfectly unyielding, it must relieve itself from the strain set up when the nucleus recedes, by violent disruption. As it is, whenever there is more matter in the interior than there is well room for, the overplus is converted into lava, and periodically transferred to the surface, and the cavities thus produced close in slowly as the crust adjusts itself to the shrinking nucleus. Lastly, it accounts in an extremely simple way for the close connection between Metamorphic, Plutonic, Volcanic, and Elevatory action; for it regards all four, not as isolated phenomena, but as different results of one common cause.

On broad general grounds then it seems as if much might be said in favour of Mr. Mallet's views; and it is really very doubtful whether, in the present state of our knowledge, it is any use trying to do more than reason in a broad general way about this class of questions. The Rev. O. Fisher has, however, attempted a minute and detailed criticism of the theory, and has on several grounds objected with considerable force to its conclusions. Mr.

Mallet has replied, and the arguments *pro* and *con* will be found in the papers quoted below.[*] In a subsequent paper Mr. Fisher has returned to the attack,[†] and has tried to strengthen his objections by some elaborate mathematical investigations. It is open to question whether either his figures or those of the original Memoir of Mr. Mallet are really of much value. In a problem of this kind, where the conditions are so complicated and the circumstances to be taken into account are so numerous, there is always considerable risk, when we attempt to reduce it to numerical calculation, that some point of vital importance has been overlooked. In the present instance it looks as if this risk is so large, that we cannot feel safe in employing numerical results in proof or disproof of the correctness of the hypothesis.

It is unfortunate that in this and many other geological questions the data are too scanty to allow of our availing ourselves of the aid of mathematical analysis; but, if this be so, it is better frankly to acknowledge the fact, and not to attempt to support or overthrow a theory by a show of numerical accuracy which has no sound basis to rest upon.

As far as providing a machinery adequate to produce the heat required for volcanic action goes, Mr. Mallet's explanation may turn out to be the right one; but when we come to his speculations as to the order of the events that have accompanied the growth of the earth into its present form, we find several of his notions to be directly in the teeth of well-established geological facts.

He thinks that during the third stage, when the surface was still too hot to allow water to lie on it, the great mass of the oldest stratified deposits[‡] were accumulated. This cannot have been, for the oldest rocks we know of contain fossils, and animal life could not have existed under the conditions which he supposes to have obtained during that period. Besides, there is nothing whatever in the structure of these rocks to indicate so tumultuous and cataclysmal a mode of formation as Mr. Mallet's views would imply.

A far more serious error is committed with respect to the fourth and fifth stages. The fourth he looks upon as a period of mountain building. It had, he admits, manifestations of igneous activity, but they were of a totally different character from those of the present day. Huge flows of lava were forced by hydrostatic pressure up fissures, but there was no action of an explosive nature. He grounds this belief on the startling statement, which will certainly be new to geologists, that the older volcanic rocks consist wholly of lava and "heated dust," and never show accumulations of fragmental matters such as are shot out of modern volcanoes by steam. He thinks this state of things may have lasted down to the date of the formation of the Chalk. It is scarcely necessary to say how completely this statement is opposed to the facts. Not to go far from home, there are in North Wales, the Lake country, and the south of Scotland countless instances of volcanic agglomerates, which are as distinctly the result of explosive action as the product of any modern volcano, and yet date far back beyond the limit fixed by Mr. Mallet.

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[*] Quart. Journ. Geol. Soc., xxxi. 469, 511. Professor Hilgard has also criticised Mr. Mallet's views, Silliman's Journal, 3rd ser., vii. 535 (June, 1874), and Phil. Mag., 4th ser., xlviii. 41 (July, 1874).

[†] Phil. Mag. (October, 1875), 4th ser., vol. i., p. 302.

[‡] I imagine this is what he means by "the assumed azoic and yet more or less stratified rocks."

Again, according to him, during the fifth stage, mountain building had ceased, and explosive volcanic action had come in. As a fact, many of the loftiest mountain ranges received their final uplift during this very period. Explosive volcanic action then can be carried much further back, and mountain building brought down much nearer to our day than Mr. Mallet seems to be aware. He allows that his stages overlap to some extent; in the case of the fourth and fifth, the overlapping is so complete that they become practically coincident. The crumpling up of the crust sometimes produces only contortion and elevation, sometimes metamorphism and volcanic products as well, but the two operations have not been confined to distinct periods, but have been going on side by side ever since the formation of the oldest stratified rock we know.

Possibly, as suggested by Professor J. Le Conte, the first formation of mountains begins while the strata are still soft enough to yield to the compressing force. They then give way easily and no heat is produced. Afterwards further crumpling goes on after the rocks have become consolidated by compression, and then crushing and fusion results.*

There is a slight modification of Mr. Mallet's theory proposed by Professor J. Le Conte, which should be noticed. Instead of supposing that the lines of weakness are fissures established at an early date, he employs the Scrope-Babbage theory to account for their production. Wherever a thick pile of sedimentary rocks accumulates, the escape of heat is checked, the surfaces of equal temperature rise, and the rocks under the combined influence of heat and water are softened, and lines of yielding are determined. Then contraction produces horizontal thrust, and its effects are most conspicuous along these lines.*

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* Silliman's Journ., 3rd ser., vii. 167.

Bearing of Mr. Mallet's Theory on Metamorphism.—Mr. Mallet's views also come in very handy to explain the constant association of metamorphism with intense crumpling and puckering. We noticed in Chapter VII. one weak point about all the explanations which look to the internal heat of the earth as the *direct* source of the heat required for metamorphism. If this were the real explanation, it would seem that the main thing requisite for metamorphosing a rock was to sink it deep enough; and that, as a rule, the greater the thickness of rock under which any bed had been buried, the more thorough would be its alteration. Of course this would not be true in every case, because other agents besides heat are wanted for metamorphism; but we should expect very generally to find those rocks most intensely altered which have been sunk deepest.

But very often this is not the case. To take one instance given by Professor Geikie: the Carboniferous Limestone of the South Wales Coalfield has at one time been covered by from 10,000 to 12,000 feet of strata, but it shows no traces of metamorphism; the rocks of the Central Highlands on the other hand are intensely altered, though at the time when their metamorphism took place they cannot have had over them more than 5,000 feet of strata.

It is clear, then, that metamorphism does not necessarily depend on the depth to which a rock has descended into the earth; but it is we have seen allied to contortion, and there does seem to be a probability that the heat due to the work of contortion may have been sufficient to produce it. We can now understand the structure of the mountain chain generalised in Fig. 138. We have there Granitic axes which shade off into Foliated Schists, and these in turn melt away into unaltered rocks; this gradual passage leads us to look upon the Granite as simply an excessively metamorphosed rock. Again, the whole mass has been subjected to folding on an enormous scale, and crumpling is more and more developed as we approach the Granite, so that metamorphism and puckering go on increasing together. It seems, then, that either the one has given rise to the other, or that both are the results of a common cause, and the latter is the explanation of the connection upheld by Mr. Mallet's theory.*

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* Silliman's Journ., 3rd ser., v. 453.

SECTION IV.—CONCLUDING REMARKS ON SPECULATIVE GEOLOGY.

With regard to the questions treated of in this chapter, the conclusion of the whole matter seems to be, that at present we know scarcely anything for certain about them. We cannot say positively what is the present state of the interior of the earth; the arguments in favour of a thick crust are very weighty, but they are far from conclusive. As to the cause of folding and contortion, and the origin of volcanic energy, we have arrived at an explanation which is to a certain extent satisfactory, but which has still too many weak points about it to allow us to look upon it as final. But such a state of uncertainty need not be a source of regret. It would doubtless be pleasant to be able to make up our minds on these fundamental questions, but on the other hand it is anything but disagreeable to reflect what a wide field of inquiry yet lies all but untouched before the geologist, and it is most encouraging to the inquirer to bear in mind what a host of opportunities are open to him of distinguishing himself. There are, besides those noticed, other problems in the speculative domain of Geology of surpassing interest, but want of space, and still more the very small way that has been made towards their solution, forbid our doing more than glance at some of them here.

Geological Time.—Under this head we may reckon the attempts that have been made to determine in years the age of the earth, or rather the time which has elapsed since it came into a condition approximately resembling the present; and also what is the probable expectation of life in the case of our planet and the system of which it forms a part. Sir W. Thomson has tried his hand at these problems, and there has been one speculation thrown out since he wrote, which may so seriously modify his conclusions, that we shall do well to refer to it.

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* The notion that the heat developed by the work of contortion has been one of the producing causes of metamorphism, has been floating about in a vague sort of way in the minds of geologists for some time. It was propounded by Mr. George L. Vose, in his Orographic Geology, in 1866.

Starting with the Nebular hypothesis as a basis, he has tried to approximate to the date of the time when the sun's heat will be exhausted. He has assumed that it has been, and will be, cooling all along. Mr. Lockyer has, however, shown that such may not have been the case, and has suggested a method by which the failing heat may have been replenished, perhaps over and over again.* Adopting views similar to those of Prout and Dumas, he thinks it likely that many of the substances which we believe to be elements, because we have not been able to decompose them, are really compounds; and that during the early periods of a star's lifetime their components existed in an uncombined state, the dissociation being perhaps due to intense heat; when the heat was so far reduced that it was no longer able to keep the elements apart, chemical combination took place, and the process may have set free a very considerable quantity of heat; in other words, when the energy which had before been occupied in preventing combination became no longer equal to the task, it appeared as sensible heat. Thus the life of a star may not have been one continuous process of cooling, but it may have every now and then fired up afresh, and the time taken to reduce it to a certain temperature may have been much longer than if it had gone on always steadily losing heat.

There has been always a clashing between geologists and physicists on the subject of geological time. The extreme slowness with which geological changes take place leads the first to demand enormous periods for the production of the results he sees around him; the speculations of the latter tend to tie down the allowance that can be granted within rather narrow limits. Possibly, if Mr. Lockyer's theory turns out to be well founded, the physicist may be able to be more liberal in his estimates, and the want of agreement between him and the geologist may be removed.

Former greater Intensity of Geological Action.—There is one other point in geological speculation too important to be passed over. The earlier geologists, we have seen, when they were in difficulty, did not hesitate to call in to their aid agencies far more powerful than those of the present day, and sometimes altogether different in kind from any we are acquainted with. Their method was profoundly unphilosophical, for they *gave no reason why* the energies of nature should have been formerly greater than now, or other than those of our own time. This school is often spoken of as the Cataclysmal or Paroxysmal School.

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* Proceedings Royal Society, xxi. 513 (Nov. 27, 1873); Chemical News, xxviii. 175 (October 3, 1873); Nature, xi. 335.

The reaction against these false views led to a school which had a tendency to run into the other extreme. Its adherents maintained not only that "the great mutations of the world are acted," but that they were acted long long ago. These geologists hardly went so far as to assert that the condition of the earth from the formation of the oldest rock down to the present time has been all along exactly what it is now; but they looked with suspicion on any proposal to call in agencies different from those of the present time. Their caution, though perhaps sometimes carried too far, was decidedly a step in the right direction. The supporters of this view have been distinguished as Uniformitarians.

Their line of argument is, only give time enough, and every change, which Geology shows us has taken place on the earth, can have been produced by the action of existing causes; there is therefore no necessity for calling in any extraordinary powers, and, if there is no necessity, it is unphilosophical to do it.

It is probably true that existing causes are quite sufficient for the production of past geological changes, *if they only act long enough.* But the time required will be of enormous duration, and the question arises, Can the assumption of an indefinite lapse of time be justified? This question we have just seen is still an open one. There is the further objection that it is not only possible, but even highly probable, that conditions different from those of our day have existed during past epochs. Indeed, if the history of the earth's development has been anything like that sketched out in the present chapter, and if there be any truth in the modern doctrines of physics, it is impossible that Uniformitarianism can be literally true even for a limited period. When the earth was hotter than it is now, all the phenomena which depend directly or indirectly on the internal heat, such as metamorphism, volcanic energy, and contortion, must have been proportionately more energetic; and if the sun was at the same time hotter, all the geological operations depending on meteorological conditions, such as denudation, must have gone on faster and on a larger scale than now. As Sir W. Thomson well puts it—"A middle path, not generally safest in scientific speculation, seems to be so in this case. It is probable that hypotheses of grand catastrophes, destroying all life from the earth and ruining its whole surface at once, are greatly in error; it is impossible that hypotheses assuming an equability of sun and storm for one million years can be wholly true."

But though the views held by the school of Uniformity cannot be exactly correct, it may be that, for the period for which they are maintained, they are not far from the truth. It is in the highest degree improbable that the oldest known rocks are really the first rocks that were ever formed, utterly unlikely that there were none before them; indeed, we may almost say that we know that this is not the case, and are certain that the time which has passed by since the deposition of those rocks, enormous as it seems to us, is as nothing in comparison with the large lapse of ages which have rolled away since the earth became tenanted by life, and denudation and deposition began their career. So that, though really the earth has been steadily losing energy all along, yet the rate of loss may have been so slow, and the interval between the formation of the oldest surviving rock and to-day may be in comparison with the whole lifetime of the globe so small, that we may practically look upon the condition of the earth as having been constant during the period with which Stratigraphical Geology deals, and may for so far back be Uniformitarians without sensible error. Of course this view involves a longer lifetime and a slower cooling than physicists have been hitherto disposed to concede; but their estimates on neither of these points are beyond question; indeed, on the first we have just seen that they may have to be materially extended.

On the other hand, a modified Uniformitarianism may be the true solution. While we resolutely reject agencies differing in *kind* from those of the present day, we may yet allow of a difference in *degree*, and admit the possibility of the rates of deposition and of the change in life having been more rapid in former times than now, and so not exceed the limits in time to which physical speculations seem to tie us down.

As far as we can at present judge, it certainly seems likely that one of these two views represents the true state of the case. But our choice does not lie wholly between them. It behoves us to be very careful how we appeal to causes differing in kind from any of which we have had experience, still we must not lose sight of the possibility of there being forces, which are periodic in their action, and yet recur so seldom that the span of human experience has not been long enough to witness even a single instance of their display. And this is not one of those purely gratuitous assumptions, unsupported by analogy or probability, the use of which brought the Paroxysmal School into disrepute. For instance, if we adopt the contraction theory of the origin of mountain chains, it is perfectly conceivable that the action of its machinery may be of this nature. The pressure may have to go on accumulating for a very long time before it can give rise to any motion; and then, when it passes a certain limit, portions of the crust may give way with a start, and a very considerable amount of disturbance may be generated suddenly; after the relief thus afforded, there may come a long interval of comparative rest till a head of pressure has gathered sufficient to make fresh disruption necessary. This explanation is *à priori* quite as likely, perhaps even more probable, than the one which supposes mountain chains to have been raised by a continuous, gentle upridging, prolonged over very long periods. Possibly the best explanation of all would be a combination of both, which imagines slow upheaval to be always going on with fits of more energetic action at intervals. Other instances might be given admitting of similar explanation, but this one must suffice here. The moral of all would be, let us be very careful how we take our own epoch as necessarily the type of all time past and to come. Experience must form the basis of our speculations, but we may fall grievously into error if we make it the limit of them.

We give, in conclusion, the titles of a few of the more important memoirs touching on the subjects which have been glanced at in this section.[*]

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[*] Sir W. Thomson, On the Secular Cooling of the Earth, Transact. Royal Soc. of Edinburgh, xxiii. 157, and Natural Philosophy, Appendix D; On Decrease in the Length of the Day owing to Tidal Friction, Natural Philosophy, Arts. 276, 830; On Dates from Terrestrial Temperatures, British Assoc. 1855, Transact. Sections, p. 18; On Geological Time, Transact. Glasgow Geol. Soc., iii. pt. 1; On Geological Dynamics, ibid., pt. 2; Prof. A. Geikie, On Modern Denudation, ibid., iii. 153; Prof. Huxley, Anniversary Address, Quart. Journ. Geol. Soc., xxv.; Prof. Ramsay, On Geological Time, Proceedings Royal Soc., xxii. pp. 145, 334; Mr. C. Sorby, Nature, ix. 388.

CHAPTER XII.

ON CHANGES OF CLIMATE, AND HOW THEY HAVE BEEN BROUGHT ABOUT.

> **" These changes in the heavens, though slow, produce**
> **Like change on sea and land."**
>
> MILTON.

OF the many remarkable events which the study of geology assures us have taken place during the past history of the earth, none perhaps are more unlooked for, or more startling when the proofs of their occurrence are fairly established, than the changes which the climate of the same spot has undergone. We find, for instance, in North Greenland, Spitzbergen, and other countries, where now the rigours of an Arctic winter are scarcely relaxed all the year round, and where the presence of a living forest tree is a sheer impossibility, the fossil remains of an abundant and varied flora, including poplars, willows, beeches, oaks, and other trees, which grow only in temperate regions, and some which perhaps indicate even a more genial climate still. And it is likely that this elevation of temperature was not a mere local accident, for it was possibly about the same time that trees pointing to a sub-tropical climate abounded in Switzerland, Germany, and Devonshire. At a somewhat later date a change exactly in the contrary direction was brought about, and the severity of Arctic regions was extended down to latitudes which now enjoy temperate conditions. Scotland was pretty much in the same condition as Greenland now, the hill countries of the Lake district of England and North Wales nourished large glaciers, and the ice-flows of the Alps and other mountain ranges pushed their way far beyond the limits which restrict their puny representatives of the present day.

When the subject of change of climate first began to attract attention, regard was paid almost exclusively to those cases where it could be shown that the temperature of a country had been formerly higher than now, and it was somewhat hastily assumed that the alteration had been all along in the same direction, and had consisted in a gradual lowering of the mean temperature of the globe; and this result was assumed with equal haste to have been brought about by that gradual cooling which the earth, if it had been originally in a fused condition, must of necessity be constantly undergoing. The former Arctic condition of Europe was ignored, either because its existence had not been placed beyond question, or because it was supposed to be due to some special and exceptional cause.

But we now know that such a view is altogether mistaken. The second instance just given of a climate different from that of the present day, shows that so far from the temperature having steadily declined as time went on, in one case at least the contrary has taken place. Our own country, after having experienced the severity of an Arctic climate, has now returned to more favourable conditions. And as the progress of geological inquiry has gone on, many such instances have been detected; and there are reasons for believing that the true story is, that alternations of genial and severe climates have been repeated over and over again during bygone ages, and that there has not been a continuous deterioration, but a rotation of climates.

The grounds for this assertion cannot be given till we come, in the second part of this Manual, to review the course of events, which a study of the rocks of the earth's crust shows to have accompanied their formation; but the causes which have given rise to these oscillations of climate can be fully understood at this point of the reader's studies, and may be conveniently considered here. We do not propose, however, to do more than offer an outline of the subject, mainly because the geologist, Mr. Croll, who has made the question almost his own, has just issued a treatise specially devoted to it.*

Of the many solutions which have been offered of the problem, How have past changes in climate been brought about? only two seem to have a sufficient show of probability in their favour to call for notice in an elementary manual. One of these supposes that a distribution of land and water, differing from that which now exists, caused corresponding differences in the distribution of climate; the other looks to certain changes, which are constantly taking place in the position of the earth's axis and the shape of the earth's orbit, for the producing causes.

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* Climate and Time in their Geological Relations: a Theory of the Secular Changes of the Earth's Climate. By J. Croll.

That the distribution of sea and land affects to a very important extent the climate of different portions of the earth is beyond question. Turn to a map of what are called isothermal lines, that is lines passing through all the points in each hemisphere which have the same temperature. If the temperature at any spot depended only on the amount of heat which that spot received from the sun, these lines must be parallel to the equator. But such is by no means the case; the isothermals are curves of the most complicated character, now stretching away northwards in long loops, and again deflected southwards by broad sweeps, and ever and anon doubling back upon themselves in apparently the most arbitrary manner. But these aberrations are all capable of explanation. Some of the most striking bends are due to the influence of ocean-currents, and no instance of this kind is more marked than where, in the North Atlantic, the isothermals are pulled out in long folds to the north-east, and a most wonderful difference in climate is produced between the eastern coast of North America and the opposite western shores of Europe.

The mean January temperature of New York, for instance, is 32°; that of the opposite coast of Portugal about 56°. Labrador, in lat. 53°, has a winter temperature of zero; that of the shores of the north-west of Ireland, on the same parallel, is about 46°; so that, while the first is almost permanently cased in ice, water but rarely freezes on the second. And the same difference is maintained as we go northwards; in fact, on our side of the ocean we must go as far north as Iceland before we meet with a winter temperature as low as that of New York. Now this marvellous contrast is due partly to the fact that a stream of cold water from Arctic seas, the Labrador Current, is always passing down along the eastern coast of North America, and still more to the fact that another current, the Gulf Stream, is always bringing from the tropics an enormous mass of heated water to bathe the western shores of Northern Europe. Now it is perfectly possible to conceive some change in physical geography, such as the upheaval of a barrier of land or the opening of a new passage, which would prevent the Gulf Stream from entering the North Atlantic, or would lead it off into another channel. In such a case the western shores of Europe would no longer enjoy their present happy fortune, and our own country would suffer somewhat the same extremities of cold that now prevail in Labrador.

Again, the distribution of land and sea affects the temperature independently of the effect it has in determining the course of currents. In the interior of large masses of land the summers are excessively hot and the winters as abnormally cold; on sea-coasts and in insular regions there is far less contrast between the seasons; so that by breaking up a continent into islands, or by allowing arms of the sea to gain access to its interior, we might very materially improve its climate.

Land and sea also produce effects on the climate of regions at a distance by means of the influence they bring to bear on the winds which blow over them. For instance, we have already mentioned that there was a time when the Alpine glaciers were far larger than at present; at that time what is now the Sahara was covered by water; the winds then that reached Switzerland from the south sucked up vapour as they blew over this broad expanse of sea, and came laden with moisture, which was precipitated as snow when they came against the cold mountain sides; hence the accumulation on the gathering ground was increased and larger glaciers were needed to relieve it. Now southerly winds blow over a parched desert, and not only bring no moisture with them, but by their warmth tend to melt the ice, so that there is a smaller supply of the material for glacier-making, and an agency tending to diminish what glaciers there are.

Led by considerations such as these, many geologists, specially Sir C. Lyell, believe that even the most extreme revolutions in climate can be accounted for by changes in the distribution of land and sea.*

That local variations, perhaps of a very excessive character, might be brought about in this way, may be readily admitted; thus, for instance, the submergence of the Sahara would doubtless tend to increase the size of the Alpine glaciers.

But the variations we have to account for were not local; the period of intense cold already mentioned, which is known as the Glacial epoch, made itself felt over the whole of the Northern Hemisphere; one era, known as the Miocene age, when genial climates extended up beyond the Arctic circle, has left its traces half way round the northern regions.

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* Principles of Geology, vol. i. chap. xii.; Hopkins, Quart. Journ. Geol. Soc., viii. 56.

Now before we can admit that cases like these were caused in the way Sir C. Lyell supposes, we must be satisfied on two points: first, that there is evidence that the hypothetical distribution of land and sea invoked to account for them did really exist at the periods in question; and, secondly, that, if it did, it was competent to produce the effects assigned to it.

Now, according to this explanation, the mild period was caused by the land being gathered around the tropics, and the polar regions being largely occupied by sea. This certainly does not seem to have been the arrangement that prevailed during Miocene times; the European deposits of that date are mainly of lacustrine or shallow sea origin, and point to the presence, not of large areas of sea, but of extensive tracts of continental land.

Again, would an accumulation of land about the equator give rise to a genial climate over the whole globe? The theory we are considering says it would, and in this way. The land, being highly heated by the tropical sun, would in its turn heat the air, which would rise and flow towards the poles, and thus there would be a constant transfer of heat from the equatorial to the Arctic regions. That this atmospheric circulation must always go on, and that it would go on in the supposed case to a larger extent than now, cannot be denied; but Mr. Croll has shown that it is very doubtful whether these aerial currents would avail anything towards mitigating the severity of the polar climate. However hot the wind might be when it left the land, it would be liable to rise to heights where the temperature is below the freezing point; all its warmth would then be stolen from it long before it reached its journey's end, and it would come down to the earth's surface in northern latitudes as a chilling and not a warming current. The proposed arrangement of land and sea might therefore bring no additional heat to polar regions; what is worse, it might prevent warm ocean-currents flowing from tropical regions towards the poles, and so might put a stop to the working of the machinery by which equatorial warmth is now largely distributed over the globe, and by the agency of which many regions that would otherwise be icy wastes are rendered habitable.

For Mr. Croll has shown that it is not currents in the air, but currents in the ocean, that are now performing this beneficent task. Wherever streams of heated water flow northwards from the tropics and spread out as they advance, they diffuse heat from their broad warm surfaces into the air above, and give rise to warm winds, the softening influences of which are felt over the adjoining countries. A great belt of equatorial land might materially interfere with these currents, which at present all take their rise in the Southern Hemisphere, and might cut off the supply of heat they are always bringing to alleviate the rigours of Arctic regions. As far, then, as accounting for the mildness of Miocene and other genial epochs goes, Sir C. Lyell's arrangement would be very liable to fail, and it is scarcely more satisfactory when it is applied to explain the cold of Glacial periods. The theory, therefore, though it may be applicable to local instances, cannot be relied upon to account for the world-wide revolutions of climate we have to deal with. At the same time, though distribution of land and sea alone seems hardly sufficient to cause such extensive changes, it may have had a share in their production, and have helped other causes in bringing them about.*

We will now turn to the second view, and see if it is more satisfactory. This explanation was first suggested by Sir J. Herschel,† but he seems afterwards to have given it up; it has since been worked out in very full detail by Mr. Croll.‡

It may save the reader the trouble of reference to a book on astronomy if we recount shortly the astronomical changes which this explanation looks upon as the ultimate causes of change in climate.

The path which the earth describes round the sun is a plane curve, called an ellipse, such as *A B P D* in Fig. 139.

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* Wallace, Nature, i. 399, 452.

† Proceed. Geol. Soc., i. 244.

‡ Mr. Croll's researches were first published in the Fourth Series of the Phil. Mag. He has in Jukes' Manual of Geology suggested the following as the order in which his papers may be most profitably read: On Geological Time, &c., xxxv. 363 (May, 1868); xxxvi. 141, 362 (August, November, 1868); On Ocean Currents, Part I., xxxix. 81 (February, 1870); Part II., xxxix. 180 (March, 1870); Part III., xl. 233 (October, 1870), xlii. 241 (October, 1871), xlvii. 94, 168 (February and March, 1874); On Supposed Greater Loss of Heat by Southern than by Northern Hemisphere, xxxviii. 220 (September, 1869). The reader will find the substance of these papers and much additional matter in the work of Mr. Croll's already referred to.

If drawn truly to scale, the real path would scarcely be distinguished by the eye from a circle, and therefore it is in the figure made much more oval than in nature, lest the reader should suppose it was actually circular. *C* is the centre, *A C P* the longest, *B C D* the shortest diameter. The sun occupies a point *S* on *C P*, called the focus. *P* is called the perihelion or point nearest to the sun; *A* the aphelion, or point farthest from the sun; *S P* the perihelion distance, *S A* the aphelion distance.

Now there are two things we have to note about the path: it is constantly undergoing changes both in shape and position. First, with regard to the change in shape; if the earth and the sun were the only bodies in the universe, the former would always pursue exactly the same path round the latter year after year; but the attractions of the other planets are always pulling the earth now this way and now that, and in this manner it comes about that the shape of its path is constantly changing at a very slow rate, so that it is at one time more oval than at another. The changes in shape can never go beyond certain fixed limits. For a long series of ages the orbit goes on getting more

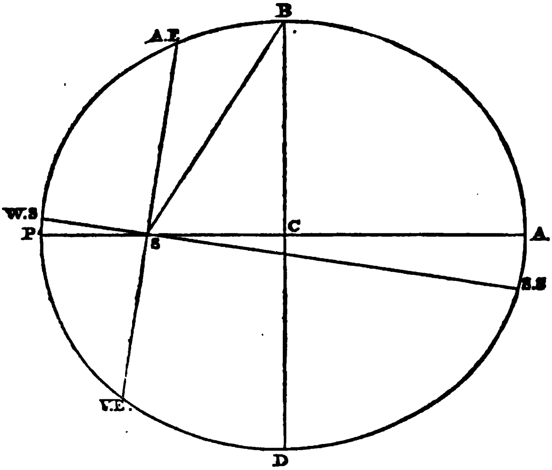


Fig. 139.—Orbit of the Earth, Eccentricity Small, Winter occuring in Perihelion.

and more oval or elliptical; then the ellipticity begins to decrease, and the orbit grows more and more nearly circular; but before it becomes actually a circle the ellipticity begins again to increase, and keeps increasing for another long epoch, when it again turns back, and begins to grow less.

This is the general nature of the change in shape of the earth's path; but we must yet consider one or two particulars more exactly. *The longest diameter, P A, is always the same*, and hence we can make the orbit more elliptical only by making *B C* shorter; in fact the orbit, while its length remains unaltered, is at some times flatter than others. But the line *B S* is equal to half the longest diameter, and must therefore always remain the same length, whatever change goes on. Now if *B* comes nearer to *C*, *B S* can keep the same length only by *S* moving towards *P*. Therefore, when the eccentricity is large, the sun is nearer to the perihelion than when it is small. *Increase of eccentricity therefore diminishes the perihelion distance, and increases the aphelion distance.*

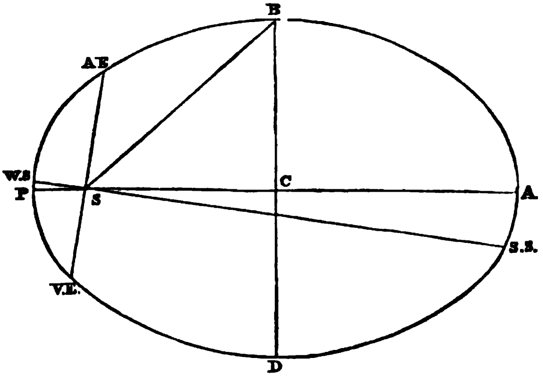


Fig. 140.—Orbit of the Earth, Eccentricity Large.

If the reader will compare Figs. 139 and 140, he will realise the effect of the change; in both the longest axis of the ellipse is the same, but in the second the curve is more elliptical, the perihelion distance *S P* is less, and the aphelion distance *S A* is greater than in the first. He must not forget, however, that in both figures the ellipticity is far greater than in the actual case.

Secondly, besides a change in shape, the path of the earth is undergoing a constant though slow change in position. If at any date the direction of the line *P S A* be determined, say by noting that it points directly to a particular star, and the observation be repeated after a time, we shall find that the line no longer points to the same star, but has moved away in the same direction as the earth revolves. This motion is called the Revolution of the Apsides, and by it the point *A* is carried round the whole orbit in about 5,000 years.

Such are the facts we shall have to bear in mind respecting the alteration in shape and the change in position of the earth's orbit. We have now to pass to a further point. A plane through the sun parallel to the plane of the earth's equator is called the celestial equator. If the line of intersection of the celestial equator and the plane of the ecliptic meets the earth's orbit in *A E*, *V E*, these points are called the Autumnal and Vernal Equinoxes. If a line through *S* perpendicular to *A E*, *V E* cuts the earth's orbit in *W S*, *S S*, these points are called the Winter and Summer Solstices. When the earth is at either of the equinoxes, the days and nights are everywhere equal in length; as the earth moves from the vernal towards the autumnal equinox, the nights are always longer than the days, the difference between day and night being greatest at the winter solstice; as the earth moves from the vernal equinox towards the autumnal equinox, the days are longer than the nights, the longest day occurring as she passes through the summer solstice. In other words, the time taken by the earth to travel from *V E* to *A E* is the winter portion, and the time from *A E* to *V E* is the summer portion of the year. Now it is very easy to see that, as long as the earth's path is not a circle, the summer and winter portions of the year must be of different lengths. Look at Fig. 139, which represents pretty nearly the present state of matters for the Northern Hemisphere. The arc *A E*, *P*, *V E* is shorter than the arc *V E*, *A*, *A E*, and, what is more, the earth moves faster over the first arc than over the second, because she moves faster the nearer she is to the sun, so that both these causes now work together to make our summer longer than our winter. Further, note that not only is our winter now shorter than our summer, but the earth is nearest to the sun nearly at midwinter, and the additional amount of heat thus obtained tends to mitigate the severity of the cold season.

The Northern Hemisphere now, therefore, is well off as regards climate for two reasons—its winter is short, and it is nearest to the sun in winter; the Southern Hemisphere is badly off, for its winter is long, and it is farthest from the sun in winter.

But now comes a point of the utmost importance: it has not always been so. We have already mentioned the motion of the earth's axis known as precession, and explained how that line is constrained to move slowly round, sweeping out a path in space like the surface of an inverted sugar-cone. Now, since the plane of the earth's equator is perpendicular to the earth's axis, if the axis moves, the terrestrial equator, and therefore the celestial equator too, must move with it; and a very little reflection will show that in consequence of the revolution of the earth's axis the line *A E*, *V E* will turn slowly round *S* as a centre. The motion takes place in the direction opposite to that of the earth's revolution, and the line makes a complete circuit in about 26,000 years. Now recollect the line *A E*, *V E* is turning at this rate in one direction, and the line *P S A* in the opposite direction, at a rate which carries it through a whole revolution in 5,000 years, and it will be clear that if we take any position of these

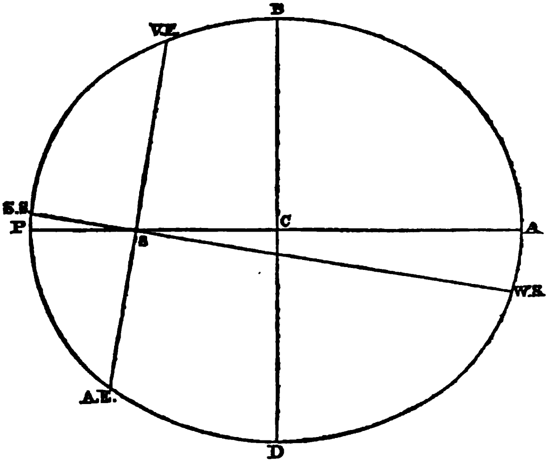


Fig. 141.—Orbit of the Earth, Winter occurring in Aphelion.

shifting lines, that in Fig. 139 for instance, after a lapse of 21,000 years they will come round to the same position again, and in half that time we shall have a state of things like that shown in Fig. 141, where the positions of the equinoxes and solstices are exactly reversed, and where the winter for the Northern Hemisphere is longer than the summer.

This will be the case with our hemisphere some 10,500 years hence, and we shall then be exactly in the position the Southern Hemisphere is in now.

The effect then of precession and the revolution of the apsides is this. Midwinter will occur at certain periods for each hemisphere when the earth is in perihelion, and the winters will then be short, and their severity mitigated by the proximity of the sun; about 10,500 years after each of these periods, the midwinter of the same hemisphere will happen when the earth is in aphelion, and the winter will then be long, and rendered more severe by the increased distance of the sun; the summer in the latter case will be short; and at first sight we might think that it would be also hot because of the near approach to the sun, but we shall see shortly that there are causes which prevent this circumstance from exercising any beneficial effect on the climate.

Now as long as the path of the earth deviates at all from a circle, the effects just described must be produced; even when its eccentricity is small, as it is at present, the hemisphere whose winter occurs at perihelion must have some advantage over the opposite hemisphere; and the greater severity of the Antarctic regions at the present day is doubtless partly owing to the winter of the Southern Hemisphere falling now very near aphelion. But the contrast will be evidently immensely greater when the eccentricity is large. Compare Figs. 139 and 140. Everything that tends to mitigate the severity of the winter in the first is present in a more pronounced form in the second, the actual length of the winter is less, and the distance from the sun in midwinter is decreased. To take an instance, our winter is now nearly eight days shorter than the summer; but if the eccentricity had its greatest value and our winter occurred in aphelion, not only would the length of winter exceed that of summer by thirty-six days, but we should be more than eight millions and a half miles farther from the sun in winter than we are now.

If, therefore, these celestial changes have anything to do with climate, it will be during periods of high eccentricity that they will produce their most telling effect. At such times the hemisphere whose midwinter occurs in perihelion will have so short and mild a winter, and so long and moderately hot a summer, that its climate will be something like a perpetual spring. The opposite hemisphere will have a long, severe winter, and a short summer; and these conditions will be transferred from one hemisphere to the other every 10,500 years. Some periods of high eccentricity have lasted long enough to allow of such a transfer having taken place several times over.

Thus much was pointed out by Sir J. Herschel, in the paper already quoted, in 1830; and he then expressed it as his opinion, that during a period of high eccentricity the effect of these secular changes would be to place each hemisphere alternately in a state approaching perpetual spring, and under a condition of burning summers and rigorous winters. He seems afterwards, however, to have felt that long periods of severe cold could not have been brought about by these causes, because however contrasted the seasons might be, the deficiency of heat during a long winter would be made up for by the large amount received during the short but hot summer. In fact the total amount of heat received during a revolution of the earth increases as the smallest diameter of her orbit decreases, and it might therefore seem at first sight as if periods of high eccentricity would give rise to an increase in the general warmth. But Mr. Croll took up the subject, and showed that, though these cosmical changes could not directly be the cause of epochs of intense cold, they must produce this result indirectly in the following manner.

The dreary winters, which will be the rule whenever the eccentricicity is high and the winter comes round when the earth is near aphelion, will be long enough to allow of enormous quantities of snow and ice gathering on land and sea every winter. At the same time, during the summer, the earth, on account of its closer approach to the sun, will receive a larger amount of heat than at present; but the summers will be so short that, even with this advantage, and supposing there was nothing to prevent the sun from exerting its full power in melting, there will not be time during the lapse of a summer for the whole of the accumulation of the preceding winter to be cleared away. The efforts then made every summer to get rid of the frozen matter will never be able to keep pace with the additions of winter, and at the end of each summer there will always be a balance of unmelted snow and ice to carry forward to the next winter's account, and the piles will grow year by year till broad areas become permanently wrapped in sheets of ice of enormous thickness.

This cause alone would favour the accumulation of great masses of ice and snow; but there are other causes which tend in the same direction, and prevent the sun from exerting its full effect in the work of melting. The presence of great masses of snow and ice will tend to keep down the summer temperature, or rather they will result in making the existence of anything deserving the name of summer impossible, in spite of the large amount of heat poured on to the earth during the part of the year which corresponds to summer. The power of the sun to heat any substance depends on the amount of sun heat which that substance can absorb or appropriate to itself. Now air can absorb scarcely any of the direct heat of the sun, and consequently the sun's rays pass through it without raising its temperature in the slightest degree. Many curious and apparently contradictory facts can be explained when this powerlessness of air to absorb sun heat is taken into account. The pitch on a ship's side off the Greenland coast has been melted by the direct rays of the sun, when the temperature of the air around was far below the freezing point. The air could not take up any of the heat, but the pitch could. In the same way, when the sun's rays have passed unaffected through the air and fall upon the ground, they meet with a substance that can absorb them; the earth becomes heated, and in its turn radiates or gives off heat to the cold air above. Now the heat radiated from the ground differs from that which comes direct from the sun in this: it can be absorbed by the aqueous vapour of the atmosphere, and it is taken up greedily, and, raising the temperature of that vapour, produces a generally genial climate. But if a country be cased in snow and ice, there will be no heat absorbed and none given back to raise the temperature of the watery vapour: the sun's heat will be all used up in the work of melting, and, as long as the icy coating remains, the temperature of the surface can never be raised above the freezing point. In such a case the ground, instead of being a source of warmth from which heat is always passing off to warm the air above, is a cold pavement, which not only has no heat of its own to give away, but tends to rob the atmosphere of any warmth it may have obtained from other sources.

Again, the sun's rays when they fall on the bare ground are very largely absorbed; but from surfaces of snow or ice a great portion is reflected back, and lost to the earth altogether.

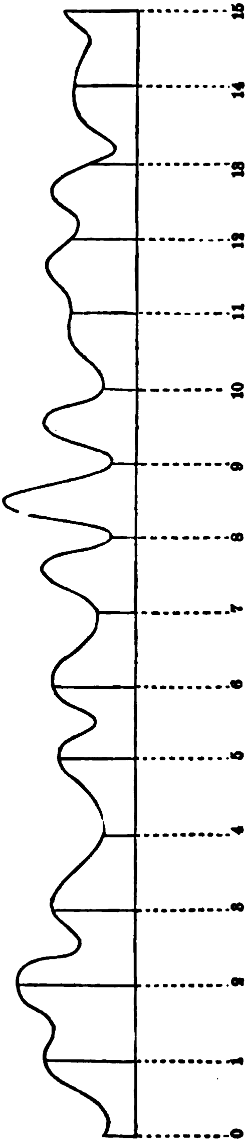
The beneficial effect which a nearer approach to the sun would tend to produce would be further neutralised in this way. The increased heat would give rise to abundant evaporation, but the chilling effect of the cold air and icy masses would condense the watery vapour, and give rise to dense fogs, which would cut off the sun's rays and prevent any melting of the snow perhaps all the summer long.

Here, one would think, we have enough to produce any amount of severity of climate; but Mr. Croll believes that there is yet another cause that would produce still more important effects. He holds that the great currents of the ocean are due to the pressure of the trade winds on the surface of the water. These trades are caused by the difference in temperature of the air in polar and equatorial regions, and if the mean temperature of one hemisphere be lower than that of the other, the trades from the first will be stronger than those from the second. Owing to this cause the south-easterly are now more powerful than the north-easterly trades, and in consequence the general set of ocean currents is towards the Northern Hemisphere. The general tendency is thus for the warm equatorial waters to be carried northwards, and raise the temperature of those northern lands whose shores are washed by them, or across which winds blowing athwart the course of the warm currents are wafted. But when the Northern Hemisphere was under glacial conditions, the Southern Hemisphere would be enjoying a mild climate all the year round, and the present arrangement of currents would be exactly reversed. The warm equatorial water would flow southwards, and our hemisphere would lose all the benefit it now derives from this source.

If the explanation just given be correct, alternations of periods of intense cold and of periods when a mild equable temperature prevailed over an entire hemisphere, must have recurred during the past history of the earth over and over again. When we come to discuss the record of bygone events which Geology presents to us, we shall find that there is evidence for such having been the case. Further, if we tabulate the values of the eccentricity for past epochs, and note the points at which after increasing for a time it begins to decrease or the contrary, we shall find that its values at these turning points are by no means all equal, and also that the periods during which the eccentricity keeps at a high or a low figure are in some cases very much longer than in others. Suppose we take a straight line and divide it into a number of equal parts, each of which represents a year, and from each of these points erect perpendiculars, making the length of each perpendicular proportional to the value of the eccentricity at the date corresponding to the point from which it is drawn, and then draw a curve through the extremities of the perpendiculars, the shape of this curve will give us an idea of the nature of the changes in the eccentricity. We shall find that we do not get a series of regular arches each of the same breadth, and each rising to the same height above *A B*, like the curve in Fig. 142, but a curve like that in Fig. 143, when the summits of the bends are some much higher than others, and the intervals between the bends very unequal in length.

Hence the cold periods will be very unequal in length, and will occur at very unequal intervals.

One more point in connection with Mr. Croll's theory remains to be noticed. According to it,



HUNDRED THOUSAND YEARS.
Fig. 143.

epochs of intense severity would alternate with periods when the temperature was equable and mild all the year round. Now one of the most puzzling facts about former changes in climate is this. In several cases where we meet with proofs of a temperate climate having extended northwards, we also find evidence of the existence of glacial epochs closely following or preceding these genial times. It seems strange that such strongly contrasted conditions should have existed so near to another, but this is exactly the result that ought to follow, if Mr. Croll's explanation be the true one. According to it, whenever there was a long continuance of a high eccentricity, each hemisphere would be alternately placed under glacial conditions and periods of perpetual spring. The Miocene epoch furnishes an admirable instance of the apparent contradiction mentioned. We have seen that during part of it forest trees could grow within the Arctic circle; during another portion there is evidence of the presence of cold severe enough to give birth to large accumulations of ice at spots as far south as the Pyrenees and Turin. Other instances will be noticed in the second part of this Manual.

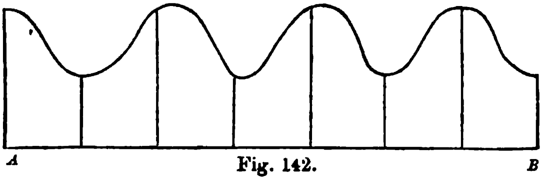


Fig. 142.

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